Wireless Networks and Mobile Computing

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Where is UT Arlington?

Education

- Ph.D., University of Central Florida, Orlando
  Computer Science (1988)
  [Washington State University, Pullman, 1985-1986]
- M.S., Indian Institute of Science, Bangalore
  Computer Science (1984)
- B.S., University of Calcutta, India
  - Computer Science and Engineering (1983)
  - Physics Honors (1980)

Founded 1909

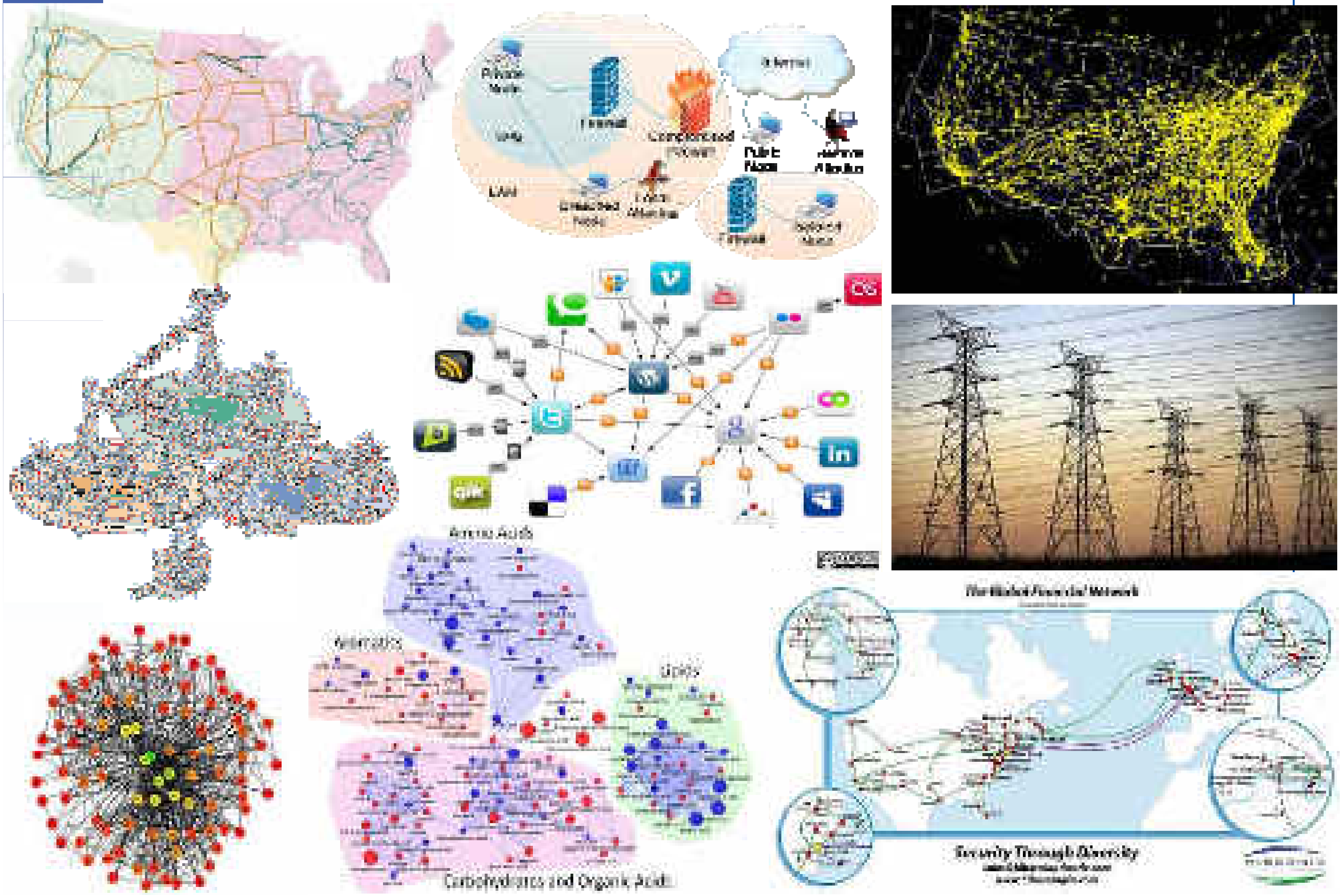
Founded 1857

Experience

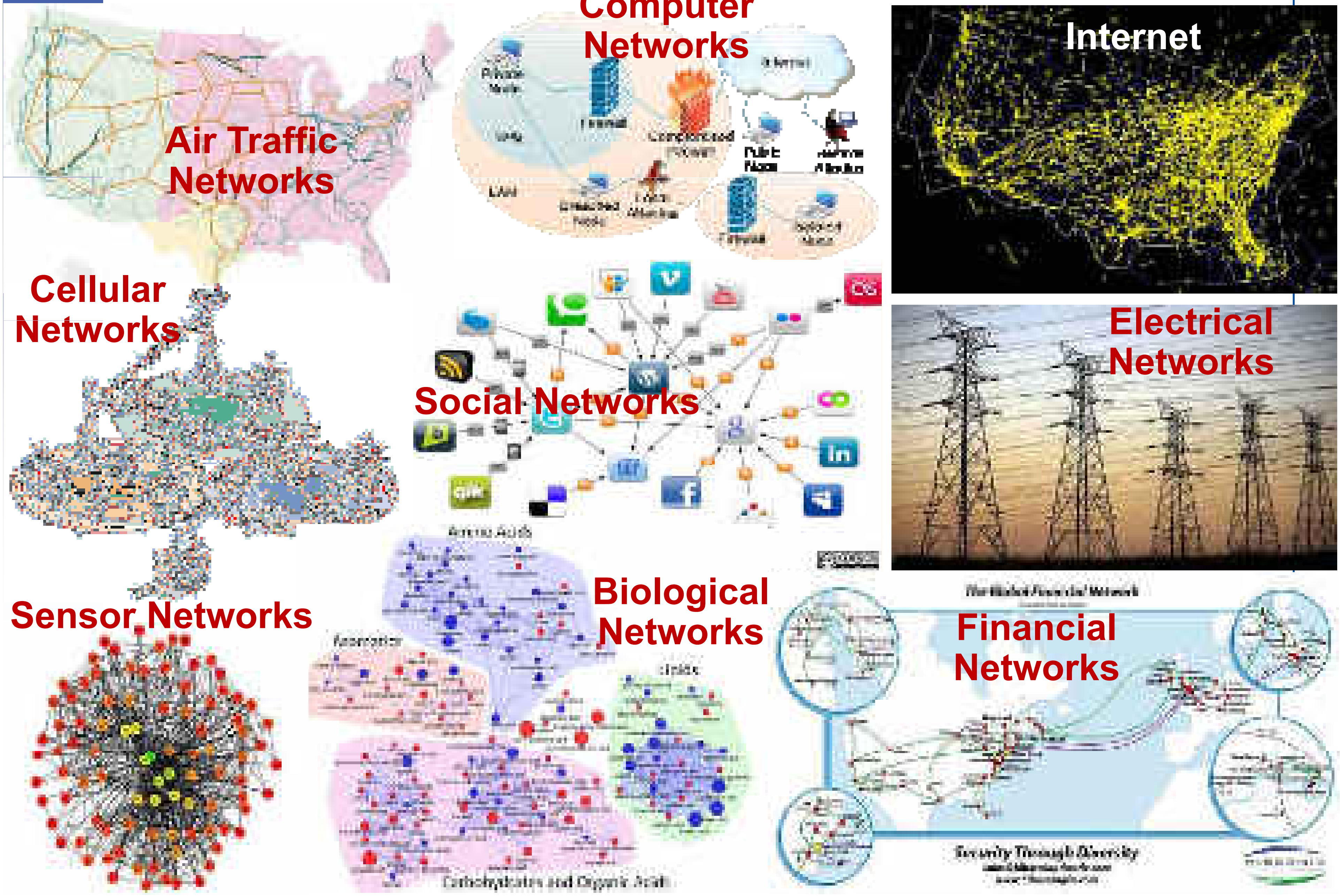
- Asst/Associate/Full Professor, Computer Science, University of North Texas, 1988-1999
- Professor, Computer Science & Engineering, University of Texas at Arlington, 1999 –
- University Distinguished Scholar Professor, UTA, 2006 –
- Founding Director, Center for Research in Wireless Mobility and Networking (CReWMaN), 2000 –
- Program Director, NSF CISE/CNS, 2008-2011

We are Networked…

We are Networked…



We are Networked…



Computer Networks

Internet

Air Traffic Networks

Cellular Networks

Social Networks

Electrical Networks

Sensor Networks

Biological Networks

Financial Networks

My Career Evolution

Distributed Computing → Mobile Computing → Pervasive Computing
(1984-) (1995-) (2001-)

Petri Nets	Cellular (3G/4G)Networks	Wireless Sensors, RFID
Parallel Algorithms	Ad hoc Networks, WLANs	Context-aware Computing
Distributed Systems	Opportunistic Networking	Situation-awareness
Interconnection Networks	Cognitive Radios	Middleware Services
Task Scheduling	Wireless Mesh Networks	Pervasive Computing
Load Balancing	Mobility Management	Smart Environments
Cluster Computing	Resource Management	Cyber-Physical Systems
P2P Networking	Wireless Internet	Smart Health Care
Grid Computing	Wireless Multimedia	Mobile and Smart Grids
Cloud Computing	Mobile Caching	Security, Privacy, Trust
Green Computing	Mobile QoS and QoE	Energy and Sustainability

- Systems Biology and Biological Network Modeling (2005-)
- Social Networks (2009-)

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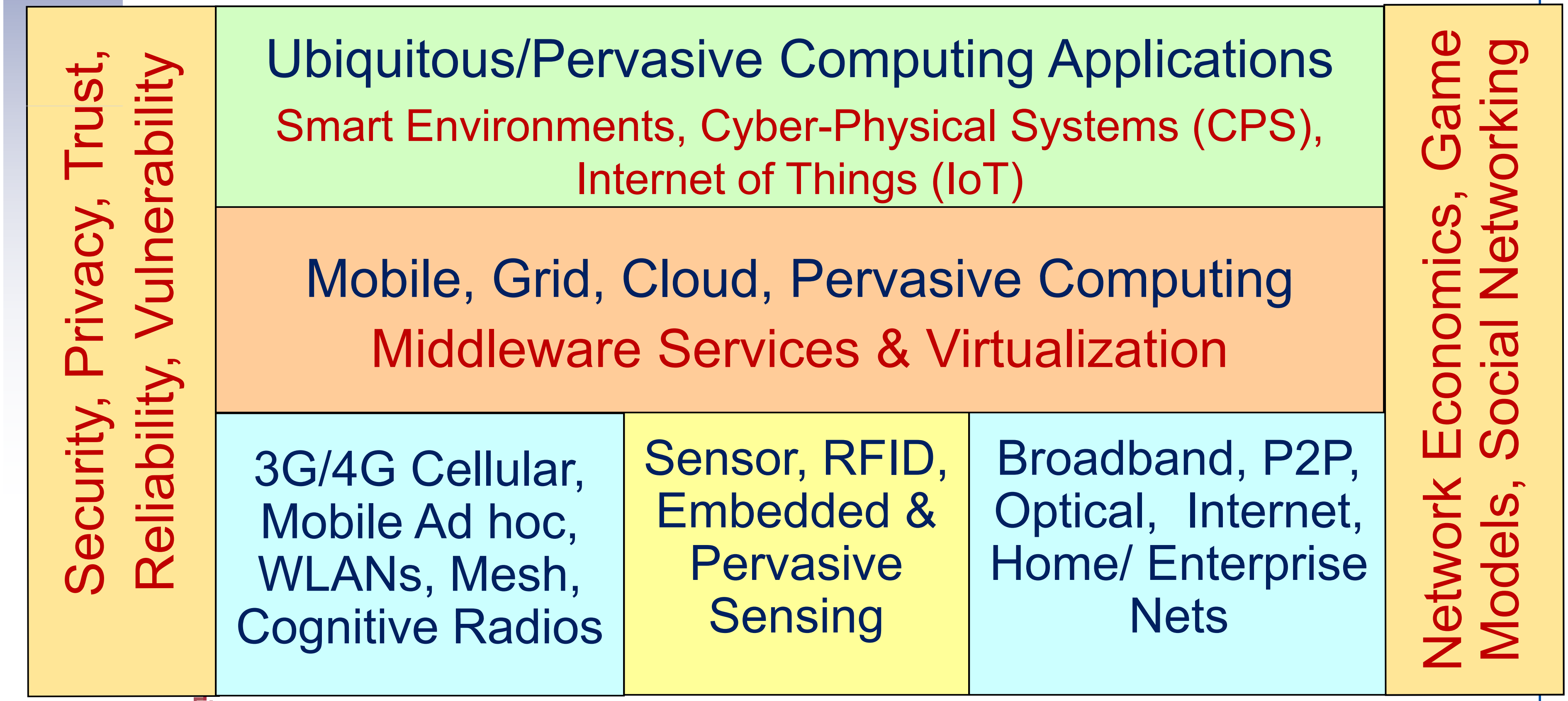
CReWMaN Scope

Architectures, Algorithms, Protocols, Modeling, Analysis, Performance Optimization, Test Beds, Experimental Study



Security, Privacy, Trust, Reliability, Vulnerability

Ubiquitous/Pervasive Computing Applications

Smart Environments, Cyber-Physical Systems (CPS), Internet of Things (IoT)

Mobile, Grid, Cloud, Pervasive Computing

Middleware Services & Virtualization

3G/4G Cellular, Mobile Ad hoc, WLANs, Mesh, Cognitive Radios

Sensor, RFID, Embedded & Pervasive Sensing

Broadband, P2P, Optical, Internet, Home/ Enterprise Nets

Network Economics, Game Models, Social Networking

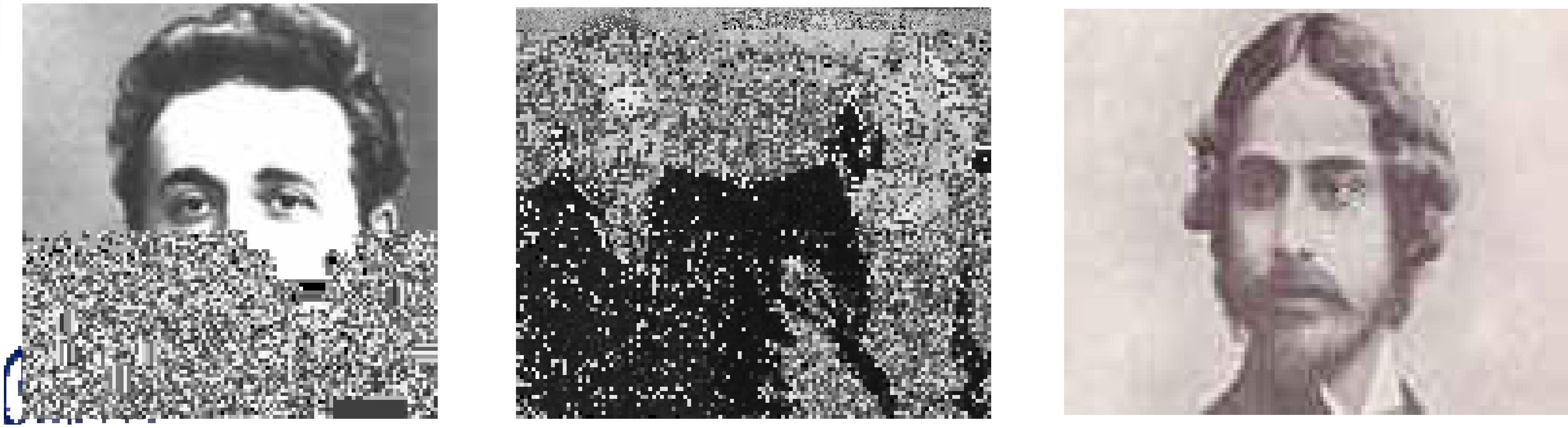
My Teaching Philosophy

"Education is the manifestation of perfection already in man."

- *Swami Vivekananda (1863-1902)*

"A *teacher* can never truly teach unless he is still learning himself. A lamp can never light another lamp unless it continues to burn its own flame. The teacher who has come to the end of his subject, who has no living traffic with his knowledge but merely repeats his lesson to his students, can only load their minds, he cannot quicken them."

- *Rabindranath Tagore (1862-1942)*
Nobel Laureate in Literature (1913)

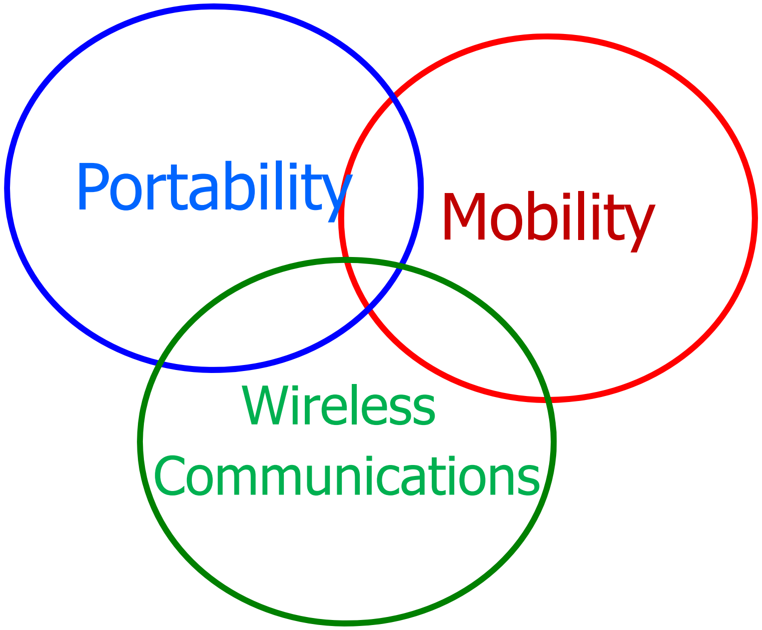


Outline

- **June 18:**
  - Wireless Mobile Communications – Fundamentals
  - Cellular Network Concepts and Channel Assignment
  - Mobility Management and Wireless Internet
  - Resource Management and Wireless QoS
- **June 19:**
  - Wireless Sensor Networks (WSNs) – Fundamentals
  - Pervasive Computing and Cyber-Physical Systems (CPS)
  - Energy-Efficient Algorithms and Protocols for WSNs
  - Security Solutions in WSNs and CPS
- **June 20:**
  - Smart Environments – Design and Modeling
  - Smart Healthcare – Middleware Services
  - Guidelines to Excellent Research
  - Mentoring and Value-Added Education

Mobile Computing: Driving Forces

- Desire to communicate and compute seamlessly while on the move, and demand for ubiquitous access to information
- Flexible use of portable devices (Smartphones, laptops, iPads, PDAs) and wireless access technologies (2G / 3G cellular, Bluetooth, ad hoc networks, wireless LANs, etc.)
- Convergence of communication and computation
- Roadmap: Sequential Computing → Distributed Computing → Mobile Computing → Pervasive / Ubiquitous Computing



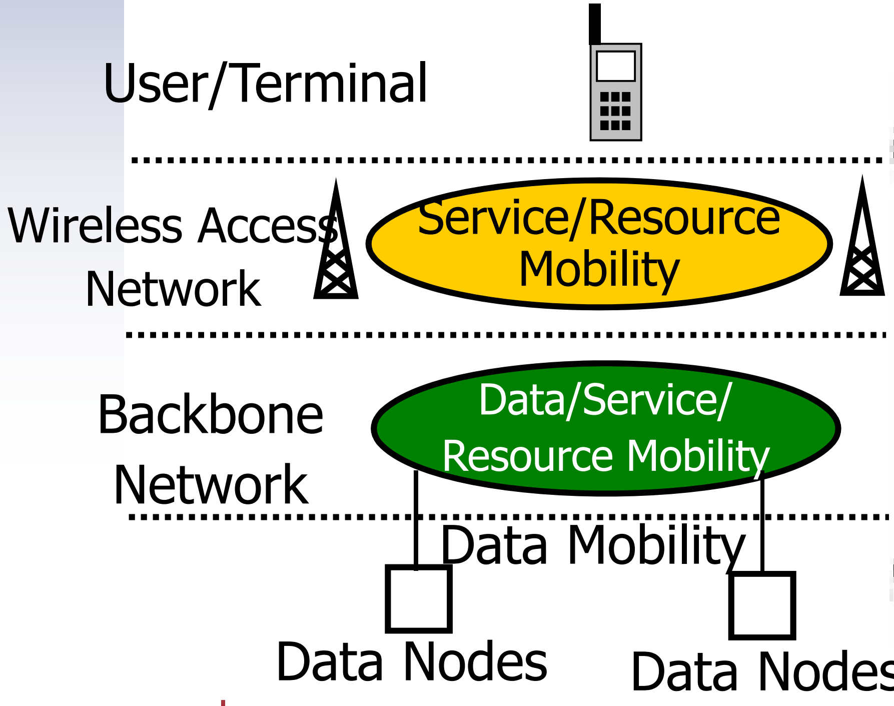
Portability

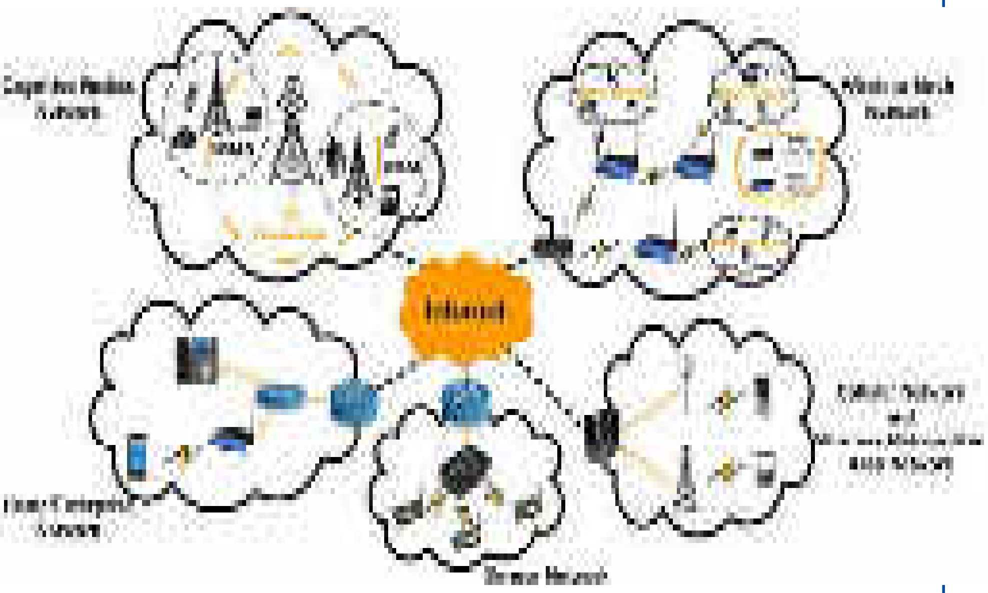
Mobility

Wireless Communications

Mobile Computing Environment

- Combination of wired backbone networks and dynamically changing wireless networks
- Wireless *base stations* (BS) linked to *mobile switching center* (MSC), that are linked through wired networks such as PSTN or Internet.

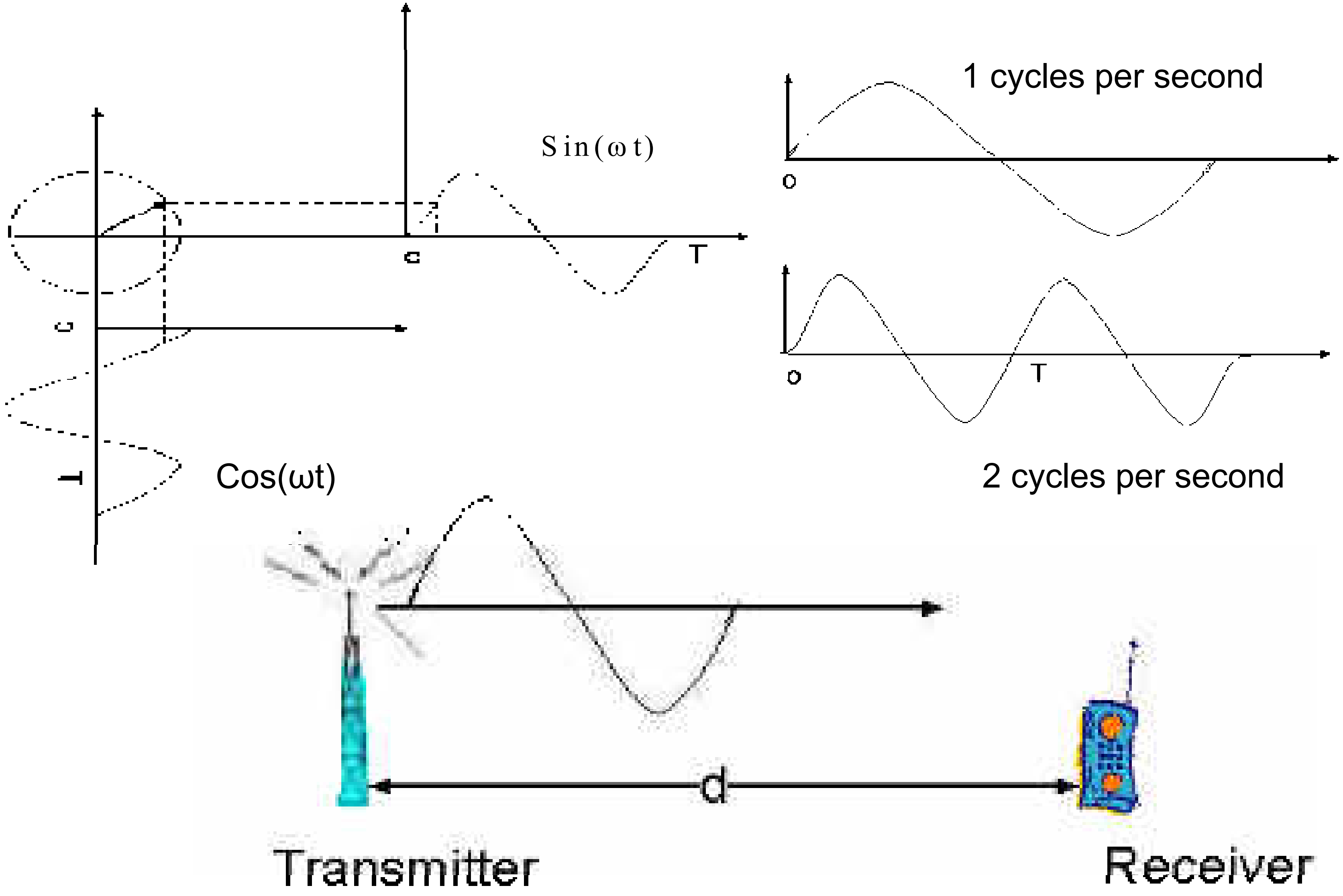




Lecture 1: Mobile Systems

- ☐ History
- ☐ Radio Signal Propagation
- ☐ Evolution of Mobile Communication Systems
- ☐ Multiple Access Control (MAC) Protocols
- ☐ Wireless Data Networks
- ☐ HW #1
- ☐ References

Radio Signal Propagation



$$\textit{Path Loss (dB)} = 10 \log (P_t / P_r)$$

Radio Signal Propagation

- **Reflection:** Owing to electromagnetic waves falling on objects with large dimensions compared to wavelength
- **Diffraction:** Caused by obstructions with sharp irregularities in the path of the radio signal
- **Scattering:** Due to obstacles in signal path with much smaller dimensions than signal wavelength
- **Multipath:** Signals reflected through buildings, mountains, trees, open ground, …
- **Fading:** Slow and fast (Raleigh model), Doppler Shift
- **Attenuation:** Signal attenuation proportional to $1/d^{\gamma}$, d = distance from transmitter, γ = path loss exponent

Path Loss Exponent (γ)

Environment	Exponent Value
Free Space	2
Urban Cellular Radio	2.7 – 3.5
Shadowed Urban Cellular	3 to 5
In Building with LOS	1.6 to 1.8
In Building Obstructed	4 to 6

Outdoor Path Loss Models

Model Name	Frequency Range	Measurement data	Terrestrial Antenna/distance	Remarks
Longley-Rice Model	40 – 100 GHz	Analytical Model uses Path Geometry & topological data	Different types	Multipath not included
Okumura Model	150 – 1.92 GHz	Measurement based Empirical model	Urban area h_{BS} : 30 – 100 m d : 1 – 100 Km	Assumes measurement data accurate
Hata Model	150 –1500 MHz	Empirical Model based on Okumara data and other measurements	Urban area h_{MS}: 1 – 10 m h_{BS} : 30 – 200 m	Correction for medium and small cities, suitable for cells > 1 Km size
Lee's Area-to Area Model	Nominal values based on 900 MHz	Empirical Model from measurements of Philadelphia, Newark, Tokyo	Flat Terrain Urban and Suburban of North America and Tokyo Urban	Computes antenna height and gain of BS and MS, transmit power
Cost 231 Hata Model	1500 – 2000 MHz	Extension of Hata Model	h_{BS} : 30 – 200 m h_{MS} : 1 – 10 m d : 1 – 20 Km	Used for PCS 1900 system
COST 231 Walfish- Ikegami Model	800 – 2000 MHz	Empirical Model	d: 0.5-5 KM	Use building height, street width building separation road orientation

d : Maximum distance between Base Station (BS) and Mobile device (MS)

h_BS : Range of BS antenna heights

h$_{\_MS}$: Range of MS antenna height

Terminology

- **AMPS** (Advanced Mobile Phone System):
  North American standard, operates in 800 and 900 MHz bands
- **GSM** (Groupe Speciale Mobile):
  Digital cellular standard in Europe
- **DCS 1800** (Digital Communication Service):
  Extension of GSM standard, operates at 1800 MHz
- **DECT** (Digital European Cordless Telecommunications):
  Cordless system supporting voice and data
- **NMT** (Nordic Mobile Telephone):
  Operates in 450 and 900 MHz bands in Norway, Sweden, Finland
- **TACS** (Total Access Communications System):
  Derivative of AMPS developed in U.K.
- **TACS/NTT**: Japanese digital transmission scheme, operates in 800 MHz and 1500 MHz bands; based on TDMA/FDD.

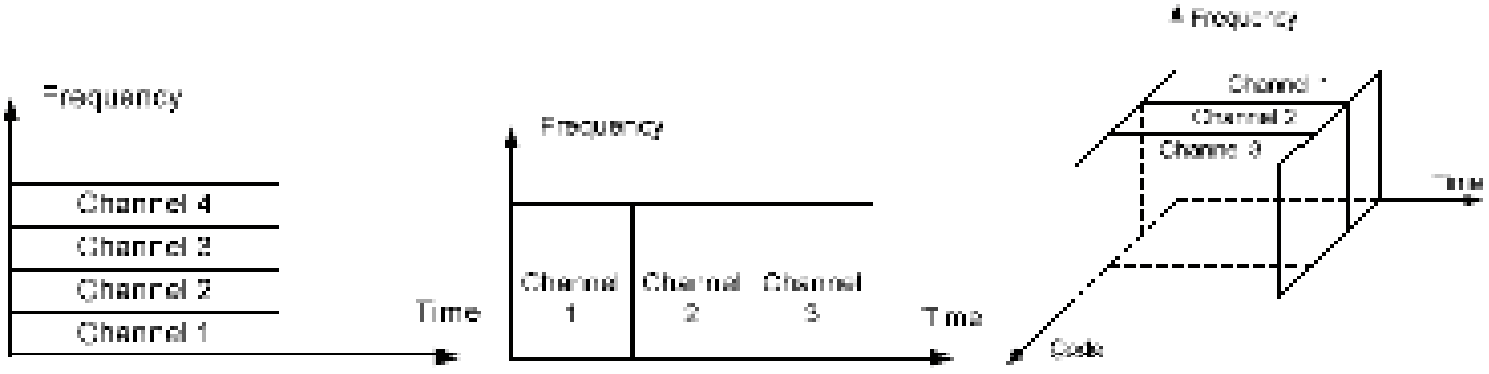
Evolution of Mobile Systems

- **1st Generation (1G): Analog Transmission**
  - AMPS
  - TACS
  - NMT
- **2nd Generation (2G): Digital Transmission**
  - GSM
  - CT2, CT3 (Cordless Telephone)
  - DECT
- **3rd Generation (3G): Unification of Technologies**
  - FPLMTS (Future Public Land Mobile Telecom Systems)
  - UMTS (Universal Mobile Telecom System)
  - IMT-2000
  - cdma2000, WCDMA (Wideband CDMA)

Multiple Access Control (MAC)

- Allows multiple users share a common RF (radio frequency) channel
- Conflict-free protocols: Static/dynamic channel allocation

  Static protocols in cellular communications
  - Frequency Division Multiple Access (FDMA)
  - Time Division Multiple Access (TDMA)



(a) FDMA (b) TDMA (c) CDMA

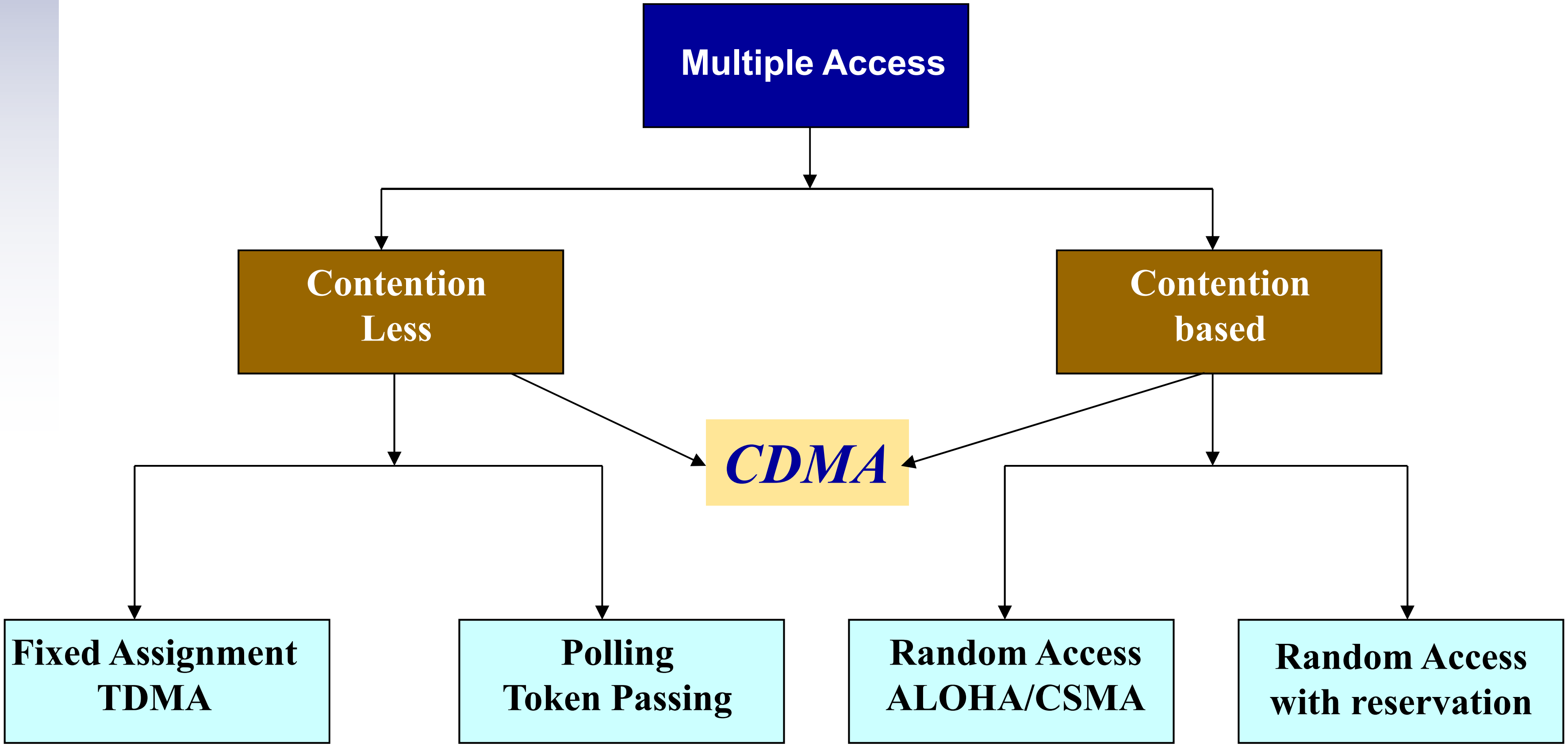
Figure 1: How FDMA, TDMA and CDMA share the media

Multiple Access Control (MAC)

- Contention based protocols need to resolve conflicts

  - *Static Resolution:* Carrier Sense Multiple Access (CSMA)

  - *Dynamic Resolution:* the Ethernet, which keeps track of various system parameters by ordering the users



Multiple Access

Contention Less

Contention based

CDMA

Fixed Assignment TDMA

Polling Token Passing

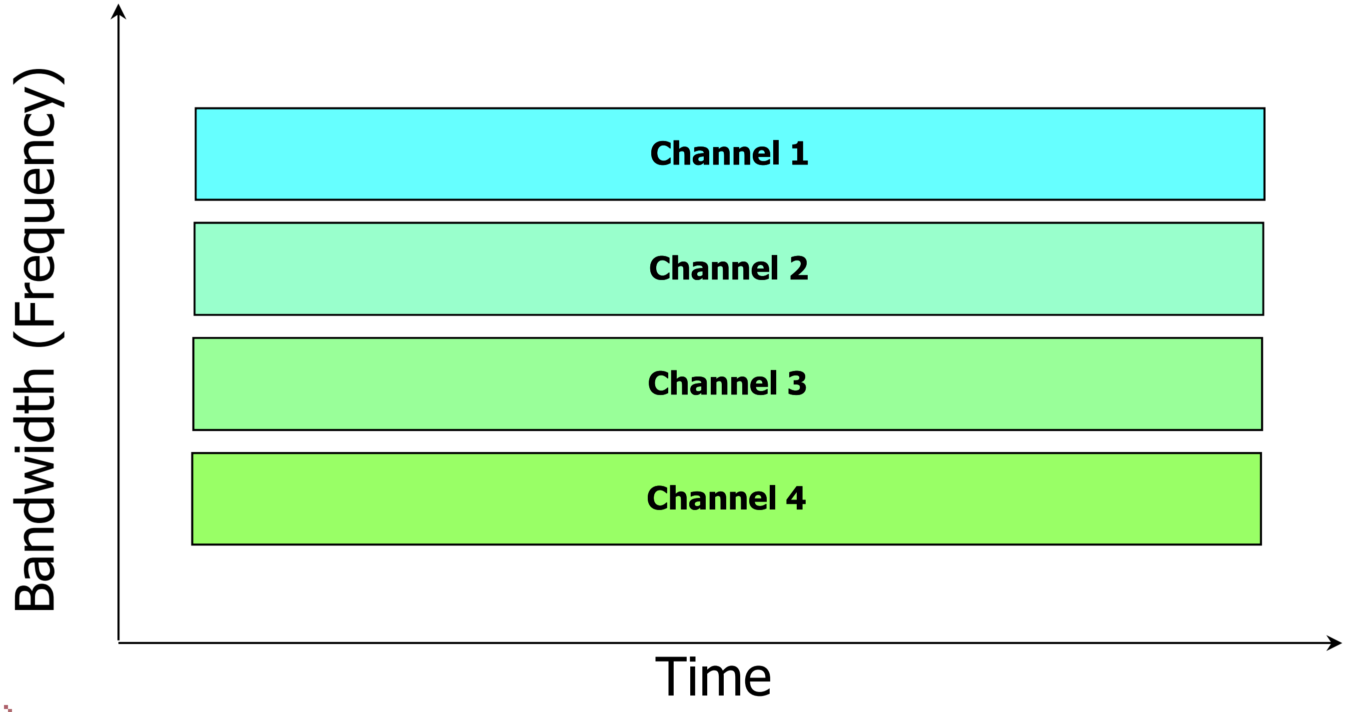
Random Access ALOHA/CSMA

Random Access with reservation

FDMA

- Provides a fraction of frequency to each user for all the time
- A channel is assigned to a user for the entire duration of a call. No other user can access the same channel during that time. When call terminates, it is re-assigned to another user
- FDMA used in 1G mobile systems:

AMPS (30 KHz channels), NMT, Japanese TACS/NTT



FDMA

- Number (N) of channels per cell to support a user population depends on the average traffic (A), average call duration and required *Grade of Service* (**call blocking probability**):

Erlang-B formula: $$E(A,N) = \frac{A^N / N!}{\sum_{l=0}^{N} A^l / l!}$$

- PSTN and PCS designed for 1% call blocking,

  Mobile phones designed for 2% blocking

- Example: 1% blocking

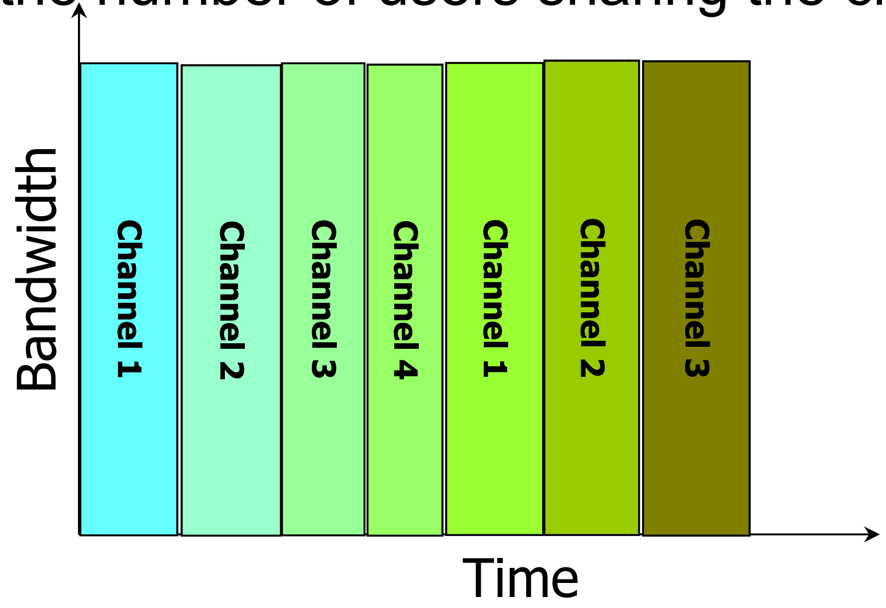
  N = 15 channels → average of 8 calls (53% occupancy)

  N = 45 channels → average of 33 calls (73% occupancy)

- FDMA systems rely on *trunk* (channel group) *efficiency*: larger pool of channels yields more efficient utilization

TDMA

- ❑ Entire frequency band allocated to a user for a fraction of time
- ❑ The whole channel is assigned to communicating users, multiplexed in time domain. Each user is assigned a time slot, when it communicates using the entire frequency spectrum
- ❑ The data rate of a channel is the sum of data rates of all the multiplexed transmissions
- ❑ Channel interference between transmissions in two adjacent slots, limits the number of users sharing the channel

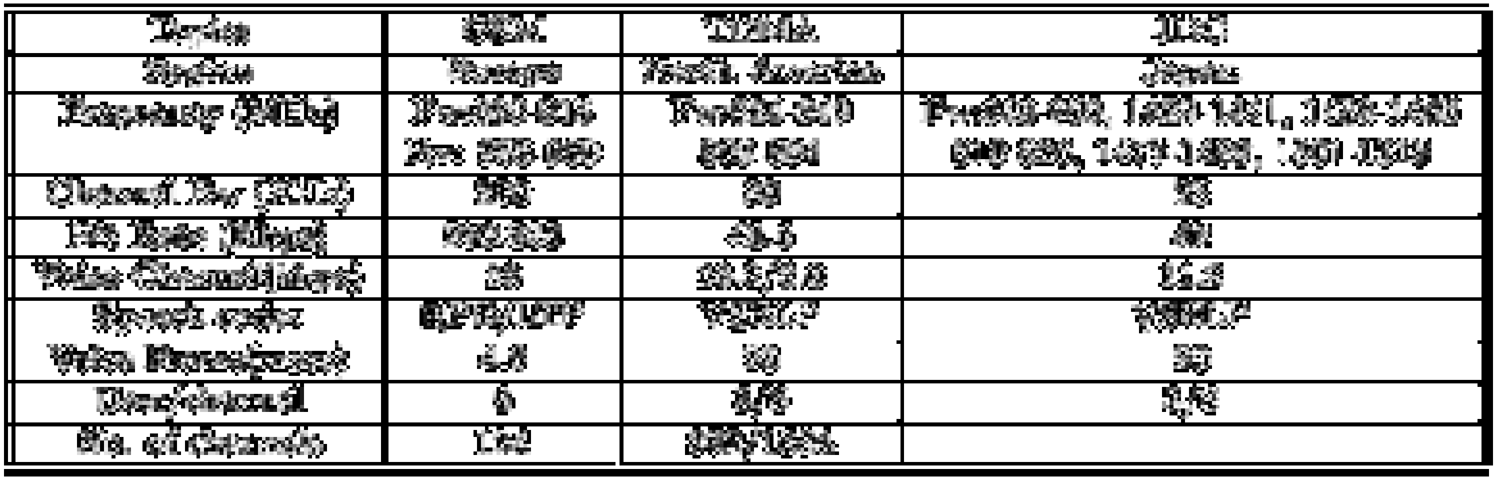


TDMA

- Synchronization of transmission is important. Imperfect synchronizations lead to channel interference
- TDMA is used in many 2G systems:
  GSM, EIA/TIA, IS-54 (digital cellular system)
- In IS-54, each 30 KHz channel divided into 6 timeslots, each with data rate 8 Kbps ➔ 48 Kbps per channel
- Two slots each for uplink traffic and downlink traffic
  (8 Kbps coded speech + overhead in 16 Kbps)
- Capacity of IS-54 is three times that of AMPS (i.e., three calls can be accommodated in 30 KHz bandwidth)

1G Systems

2G Systems



GSM Channel & Frame Structure

Uplink Spectrum: 890-915 MHz
Each Channel: 200 KHz
Guard band: 100 KHz at either ends
Total # of Uplink Channels: 124

Downlink Spectrum: 935 -960 MHz
Total # of Downlink Channels: 124

Each Channel supports *8 Time slots*

Data Rate of Time slot: 270.833 Kbps

Transmission in a *burst mode* of duration: 0.577 μsec

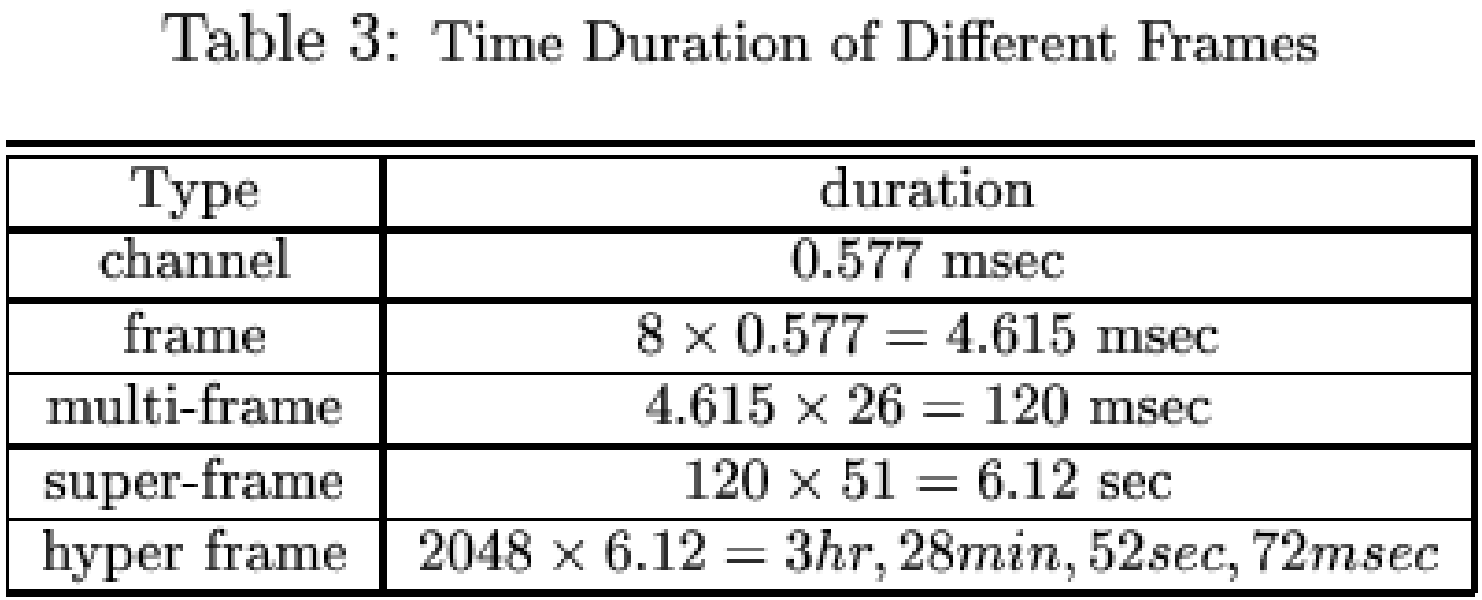
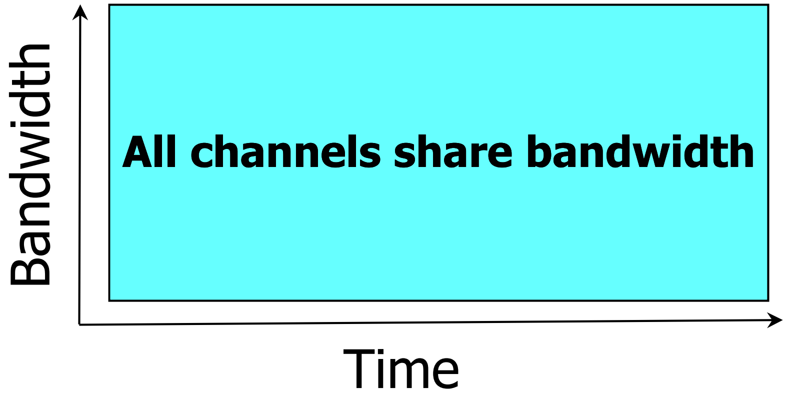


Table 3: Time Duration of Different Frames

Type	duration
channel	0.577 msec
frame	$8 \times 0.577 = 4.615$ msec
multi-frame	$4.615 \times 26 = 120$ msec
super-frame	$120 \times 51 = 6.12$ sec
hyper frame	$2048 \times 6.12 = 3hr, 28min, 52sec, 72msec$

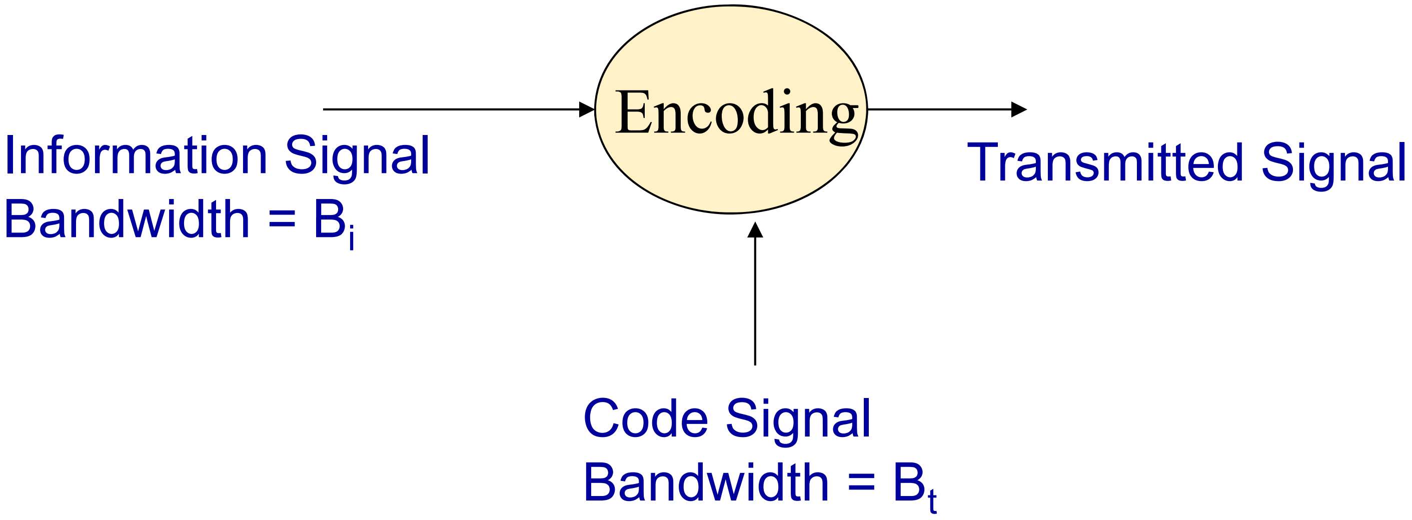
CDMA

- Provides each user a fraction of bandwidth for a time slot
- *Spread-spectrum* (SS) technique – allows multiple users to share the same channel by multiplexing transmissions in code space. Different signals from different users are encoded by different codes (keys) and coexist both in time and frequency domains
- A code is represented by a wideband pseudo noise (PN) signal
- When decoding a signal at the receiver, due to low cross-correlation of (orthogonal) codes, other transmissions appear as noise. This enables multiplexing of multiple transmissions on same channel with minimal interference
- Maximum allowable interference (from other transmissions) limits the number of simultaneous transmissions on the same channel



Principles of Spread Spectrum

Spreads original signal power
over larger spectral width
than data signal



Information Signal
Bandwidth = B_i

Encoding

Transmitted Signal

Code Signal
Bandwidth = B_t

Processing Gain $G_p = B_t / B_i$

Receiver correlates received signal with a replica of code signal to recover original information signal

CDMA Spreading

- Direct Sequencing (DS):

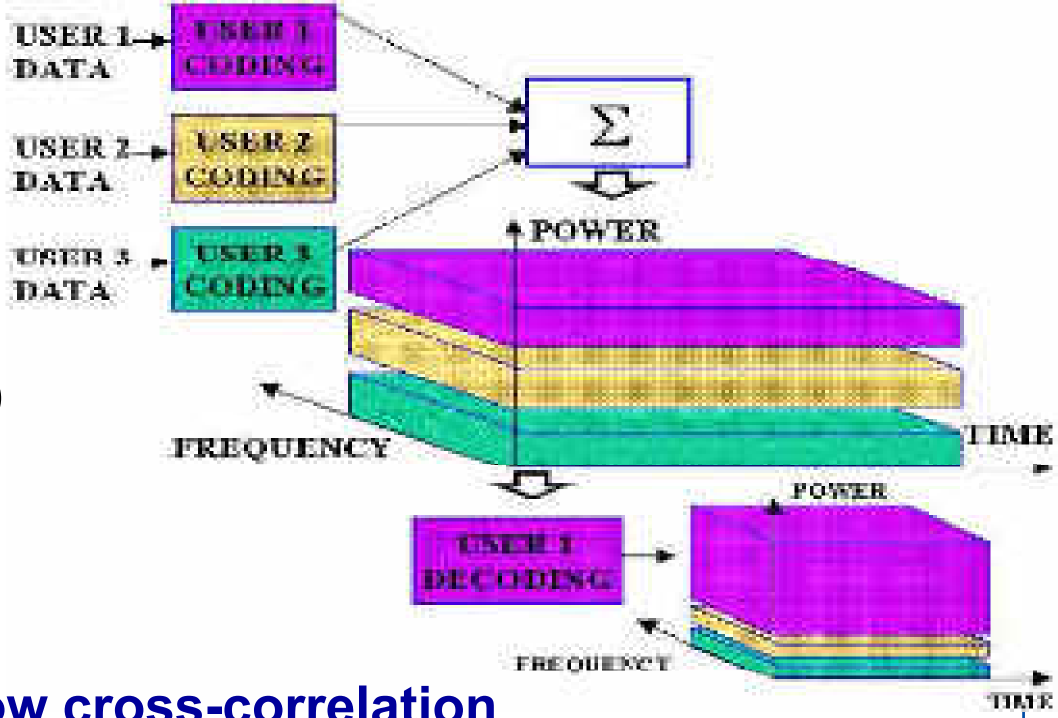
  Narrow band data signal multiplied by a wideband pseudo noise (PN) signal (code). Multiplication in time domain translates to convolution in spectral domain, resulting in wideband signal.

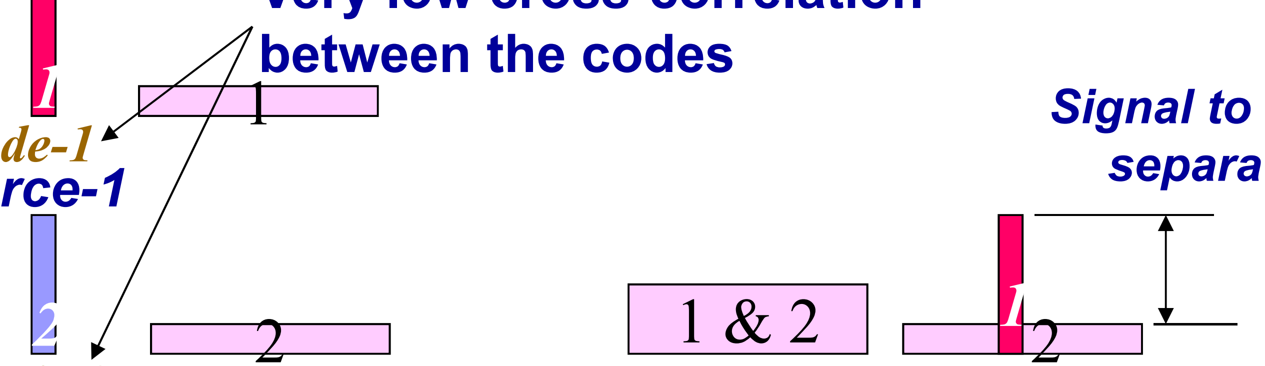
- Frequency Hopping (FH):

  Carrier frequency hops among a set of frequencies according to some pseudo random sequence (code). The set of frequencies spans a large bandwidth – transmitted signal appears as largely spread.

CDMA Spreading

- Unique codes spread base band data before transmission
- Correlator at receiver de-spreads the signal (narrow band pass filter)
- Chip rate – rate of a spreading code





Information Signal

Very low cross-correlation between the codes

Code-1

Source-1

Code-2

Source-2

Transmitted Signal

Received Signal

Received Signal after correlation with Code

Signal to Noise separation

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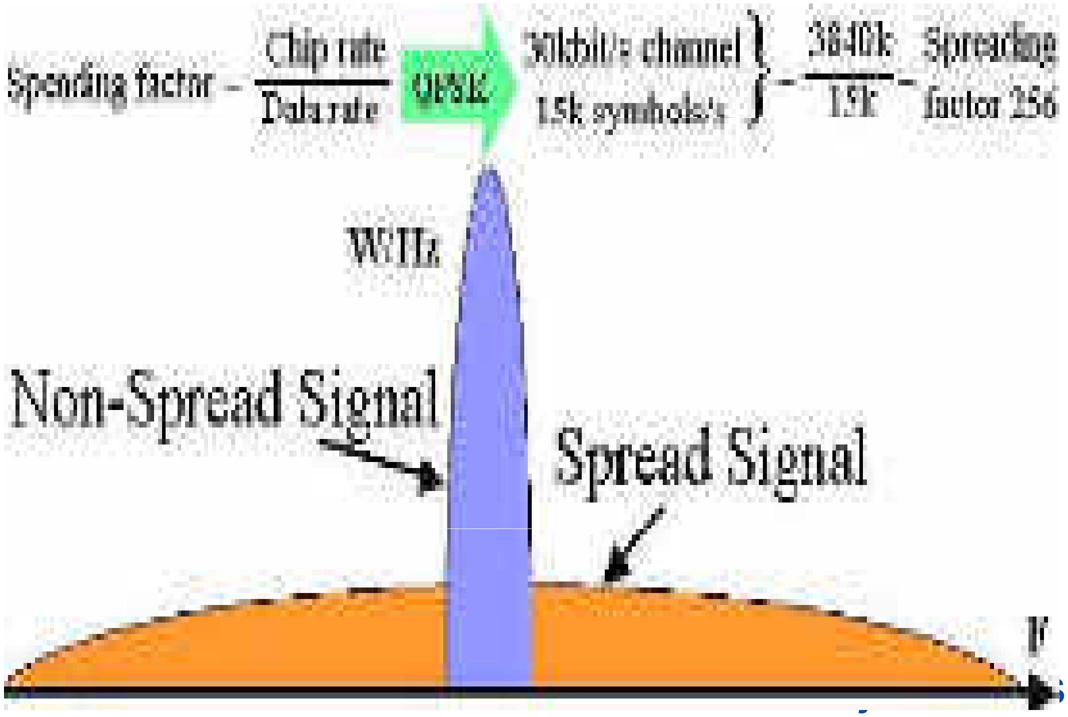
CDMA Networks

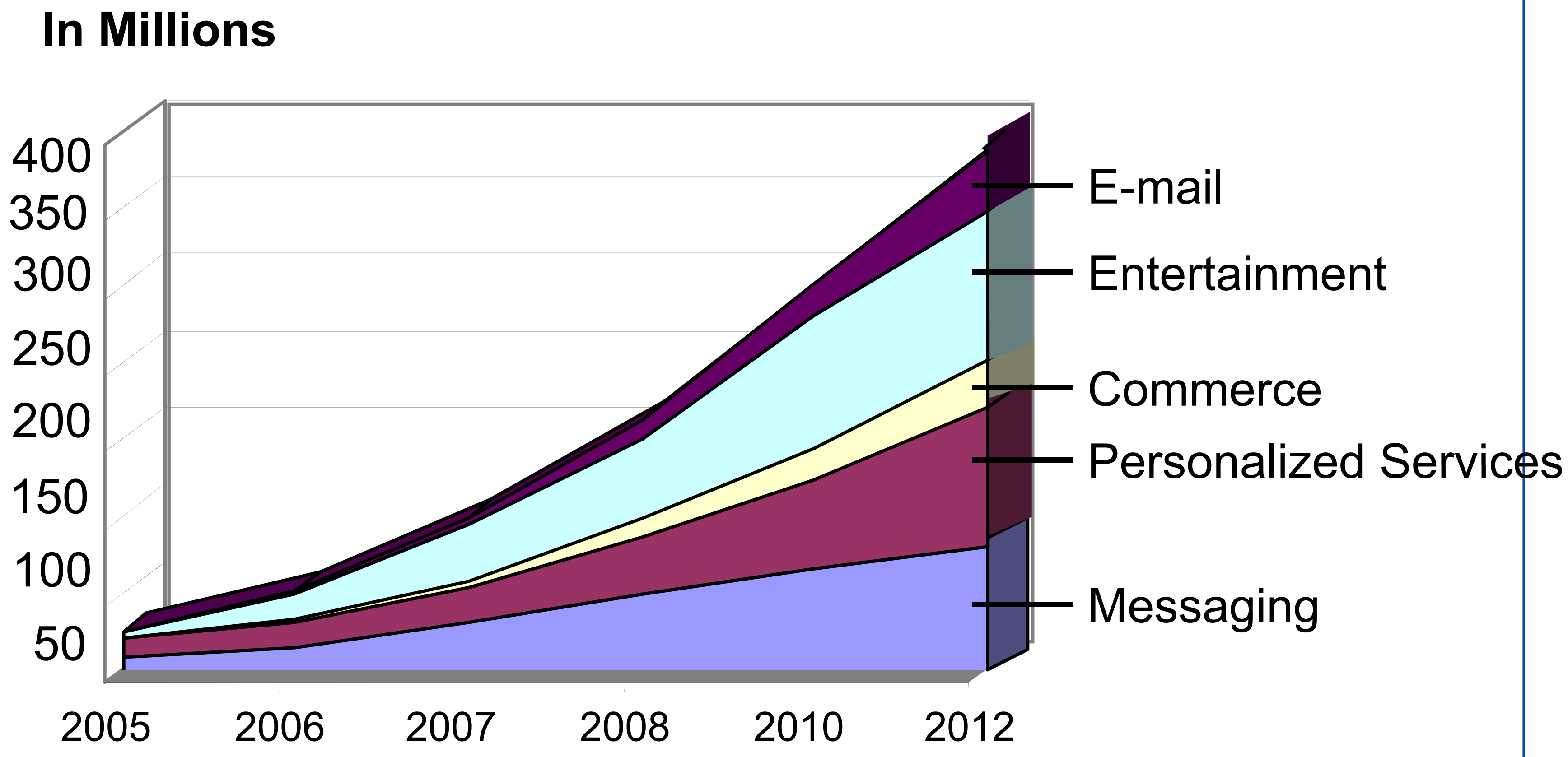
- Wideband CDMA uses Direct Sequence spreading (combines base band info. with high chip rate binary code)
- Spreading factor is the ratio of chip rate (UMTS = 3.84Mcps) to the base band data rate
- Spreading factors vary from 4 to 512 in FDD UMTS
- Spreading gain expressed in dBs (Spreading factor 128 = 21dB gain)



Wireless Data Networks

- 2G systems (voice-centric, data loss unimportant)
  - GSM
  - IS-54 TDMA
  - IS-95 CDMA
- 2.5G systems (mainly voice, low data rate)
  - CDPD (Cellular Digital Packet Data): 19.2 Kbps
  - HSCSD (High Speed Circuit-Switched Data): 76.8 Kbps (GSM)
  - GPRS (General Packet Radio Service): 114 Kbps
  - IS-99 CDMA, IS-136 TDMA
- 3G standards (data-centric, high data rate)
  - UMTS, EDGE, WCDMA, cdma2000, UWC136, IMT2000, HSPDA
  - Data rates: Vehicular (144 Kbps), Pedestrian (384 Kbps)
  - Indoor 2 Mbps for 3G (Up to 100 Mbps in 4G)

Wireless Data Growth



More Than 350 Million Consumer Data Users Expected in North America by End of 2013

3G System Features

- ❑ Global System (all existing systems & terminal types)
- ❑ Worldwide market and off-the-shelf compatible equipment
- ❑ Worldwide common frequency band and roaming
- ❑ Audio, video, packet data and multimedia services
- ❑ High service quality
- ❑ Flexible radio bearers
- ❑ Bandwidth-on-demand capabilities
  (low rate paging messages, high rate video or file transfer)
- ❑ Improved security
- ❑ Distributed and coherent network management
- ❑ Compatibility of services within IMT-2000
- ❑ Scalable

… More on 3G

- Objectives
  - High-quality speech using low bit rates
  - Advanced addressing mechanisms
  - Virtual home environment for service
  - Seamless indoor and outdoor
  - Dual mode/band of operation of GSM/UMTS in one network
  - Roaming between GSM and UMTS networks

- Technical Challenges
  - Mobility and Automatic Adaptation to various Standards, Infrastructures
  - Air-Interfaces: Cope with variable, asymmetric data rates with different QoS requirements
  - Radio Resource Management: Smart dynamic resource allocation, Efficient modulation techniques

Wireless Access Capabilities

	Freq. Band	Data Rate	Range	Efficiency
GPRS	800 –9000 KHz	CS2; 13.2X8 kbps	2-5 Km	0.184
EDGE	900 KHz, 2 GHz	Ped: 384 Kbps Veh: 144 Kbps	183 m 1868 m	0.9495 1.038
UTRA		Ped: 384 Kbps Veh: 144 Kbps	297 m 2477 m	0.45/0.67 0.26/0.29
WLAN IEEE 802.11b	2.4 and 5 GHz ISM	1 Mbps 2 Mbps 5.5 Mbps 11 Mbps	198(92) m 159(74) m 125(58) m 99(46) m	
Bluetooth	2.4 GHz ISM	64 Kbps Syn 433.9 Kbps ACL 723+57 Kbps ACL	4.64 m	

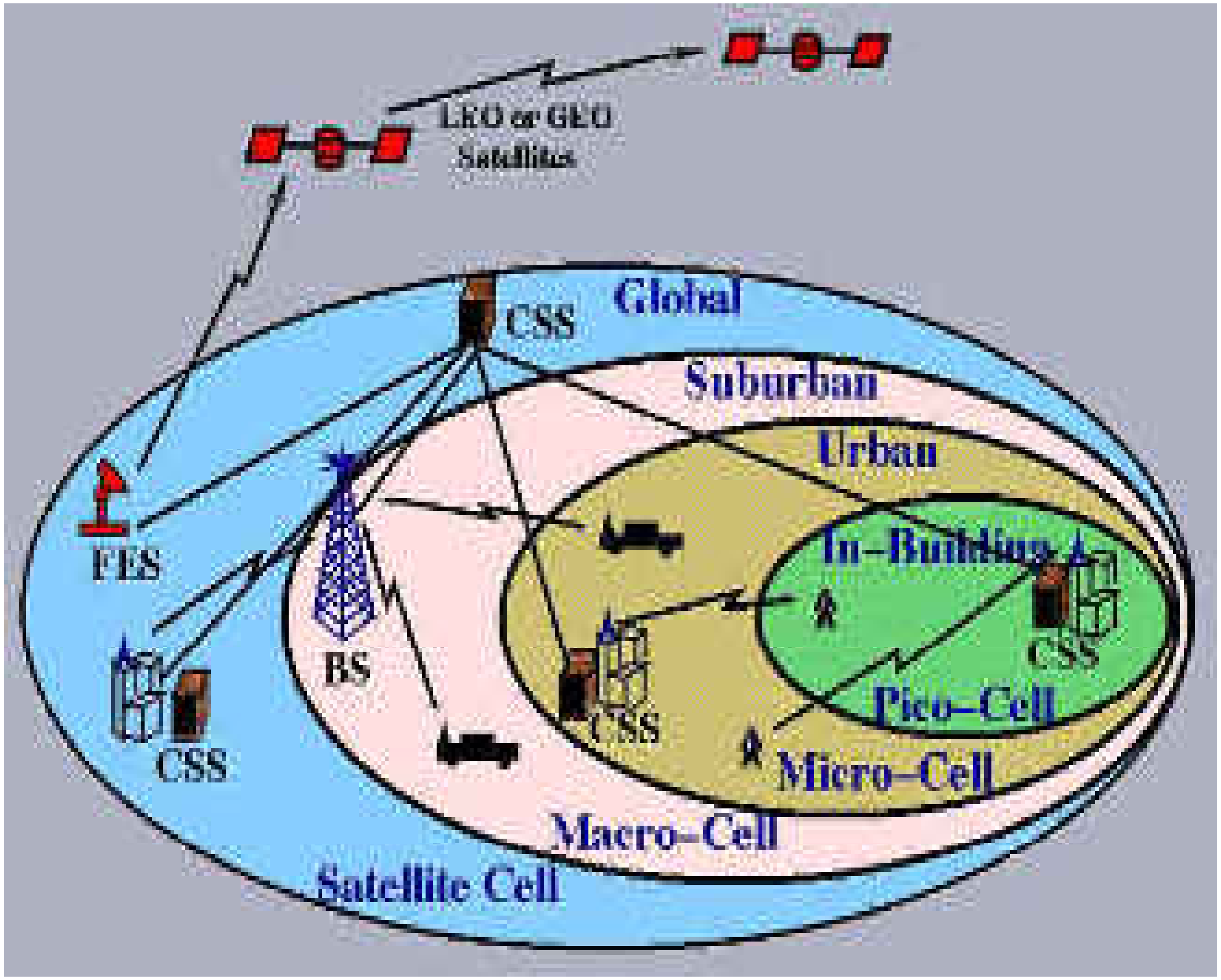
Comparison of 2G and 3G Systems

	2G	3G/4G
Digital Technology	Modulation, Speech, Channel Coding	Increased Use, Software Radios
Environments	Vehicular, Pedestrian, FWA	Vehicular, Pedestrian, Office, FWA, Satellite
Frequency Bands	800MHz, 900MHz, 1.5GHz, 1.8GHz	WRC'92, WRC'95
Services	Low/Medium Rates; Primarily Voice, Data	Higher Data Rates; Circuit/Packet Switched Multimedia Services
Roaming	Restricted	Global Roaming

Research Challenges in 3G

Protocol Layer	**Research Challenges**	**Research Approach**
Devices (Terminals)	Long talk time, lower power, size, and cost increased functionality	Low-Power VLSI (wireless DSP), Advanced Architectures
Physical (Modem)	Multipath, co- and adjacent channel interfaces	Coding and equalization Anti multipath techniques: Antenna Diversity, Multi-tone, and Spread spectrum
Link	Fair and efficient channel-sharing Privacy of sensitive user information Reliable delivery to higher layers	Packet-based MAC procedures (e.g., RAMA) Encryption of raw data Link layer handoff with state-exchange (AIRMAIL)
Network (largely control plan issues)	Meet the service requirements for voice, data, video, and image traffic Develop a locator service Secure call-setup (signaling) Limit signaling load	Resource allocation and routing procedure for setting rapidly configurable virtual circuits Fast query and updates in address data bases Authentication procedure Distributed processing & data management
Transport	Reliable data transport service Acceptable transport services for voice, video and image	Retransmission and flow-control procedures for efficient operation in a mobile environment Procedure for hand-off of context-information Adaptation for removal of jitter in real-time traffic
Session	Graceful degradation of real-time traffic	Embedded encoding for voice and video
Application	Higher quality speech & video Location-based services Person locators Wireless business/Home nets	Speech/video compression Mobile “OS” Distributed data bases Authentication procedures
Service	Increased Availability (i.e., capacity)	Microcells Less BW per user (source/channel coding) Greater frequency reuse (CDMA, DCA, interference cancellation)

Beyond 3G



- Hierarchical cell structure
- Vertical handoff
- Global roaming

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Lecture 2: Cellular Concepts

- ☐ Radio Frequency Reuse
- ☐ Cellular Architecture
- ☐ Capacity Enhancement
- ☐ HW #2

Motivation

- Limited amount of frequency spectrum allocated by FCC (Federal Communications Commission) and remarkable growth of mobile wireless users
- Uplink transmission from mobile: 824-849 MHz, Downlink transmission from base station: 869-894 MHz
- With 30 KHz channel spacing, the allocated frequency band accommodates 832 duplex channels
- Number of simultaneous calls (capacity) greatly exceeds total number of frequencies (channels)

Wireless Spectrum Limitation

Example:

- 6 million people in a city
- 25% penetration rate of wireless services
- 50 mErlang/user traffic during busy hour
- Total busy-hour traffic = 75,000 Erlang

- 30 KHz bandwidth for one-way channel
- 90% average occupancy of channel
- Total bandwidth required = 5 GHz

Impossible to have such huge spectrum

Why Channel Reuse?

- Frequency Reuse:

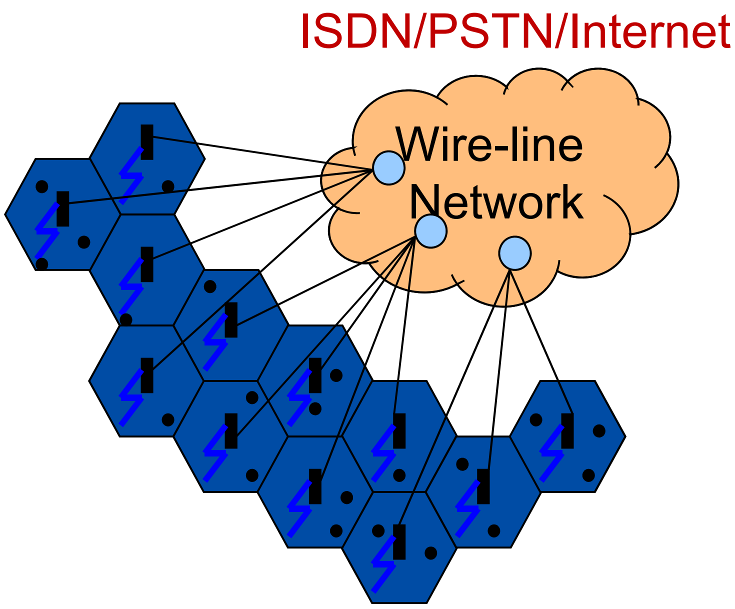
  Use same carrier frequency / channel at different areas (*cells*) avoiding co-channel interference

- Cell:

  Geographic area divided into cells, each serviced by an antenna called base station (BS). Cells can be hexagonal, square, triangle, circular, ...

- Mobile Switching Center (MSC):

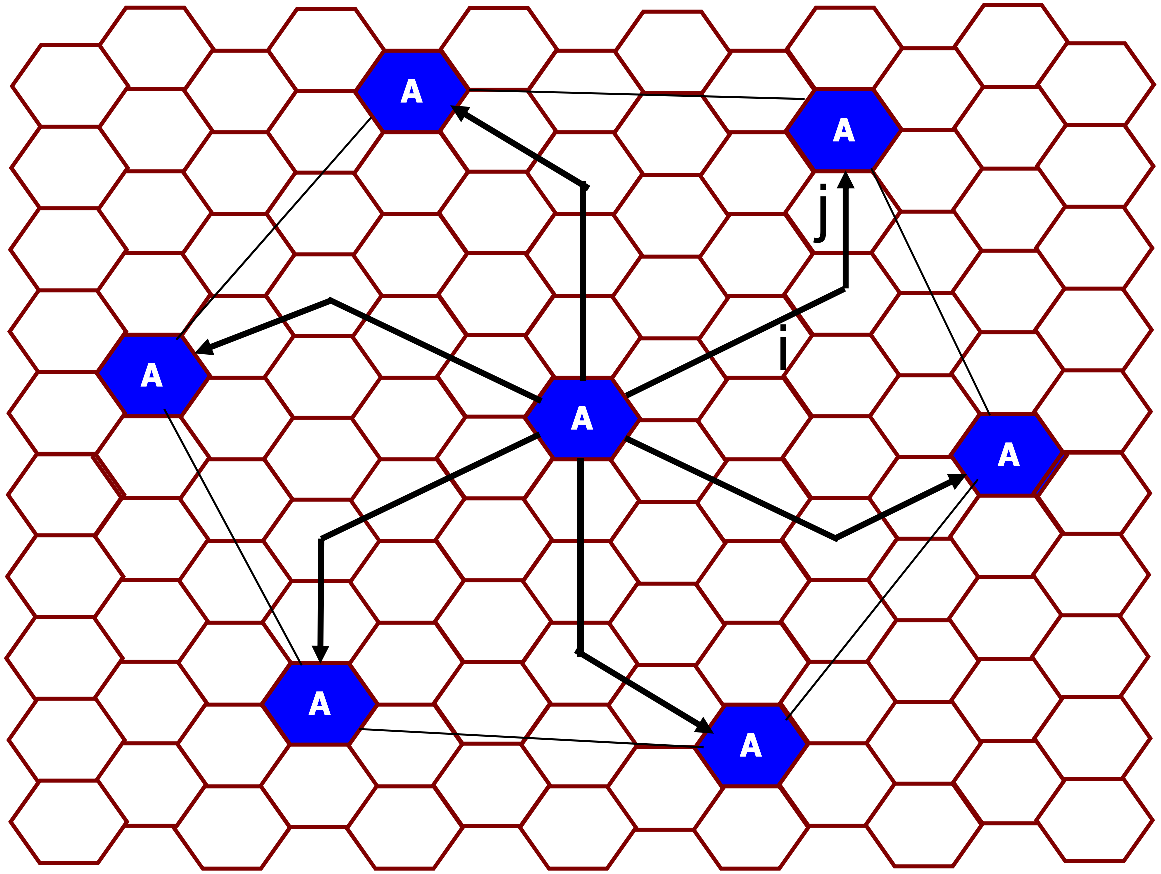
  Controls BS and serves as gateway to the backbone network (PSTN, ISDN, Internet)



⬢ Cell
▮ Base Station (BS)
• Mobile unit
ϟ Wireless Links
/ Wired Links
○ Mobile Switching Center (MSC)

Where to Reuse Frequency?

- Determine minimum distance at which a frequency can be reused with no interference, called the *co-channel reuse distance* (D)
- Signal-to-interference ratio (C / I) is index of channel interference



Shift Parameters
i = 3, j = 2

Nearest Co-channel Cells

- Determine two parameters *i* and *j*, called shift parameters
- Start from a cell, move *i* cells along one of 6 sides of hexagon. Turn clock-wise by 60 degrees and move *j* cells. The destination is the nearest co-channel cell

  (For each cell, two sets of 6 nearest co-channel cells)

- Repeat pattern to form clusters of cells. Each cell within a cluster is assigned a different set of frequencies. Such a cluster is called a frequency reuse (or compact) pattern
- Number of cells in a reuse pattern is given by

$$N = i^2 + i\,j + j^2$$

- Possible values of N are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, ….. for *i*, *j* = 0, 1, 2, …

Cluster Size

- ❑ D = distance between two co-channel cells
- ❑ R = cell radius
- ❑ Co-channel reuse ratio D / R = $\sqrt{3N}$ for hexagons
- ❑ Signal-to-interference ratio: C / I ≈ $(D / R)^4 / 6$
- ❑ If minimum allowable C / I is known, D / R and the size (N) of the reuse pattern can be derived

Parameter	Cluster Size (N)	Reuse Ratio (D / R)
i = 1, j = 1	3	3
i = 1, j = 2	7	4.58
i = 2, j = 2	12	6
i = 1, j = 3	13	6.24

Mobile System	(C / I) min	Reuse Ratio (D/R)	Cluster Size (N)
AMPS	~ 18dB	~ 4.6	7
GSM	~ 11dB	~ 3.0	4
IS-54	~ 16dB	~ 3.9	7
CDMA	~ - 15dB	~ 0.7	1

Co-Channel Interference

:

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{n_c} I_i}$$

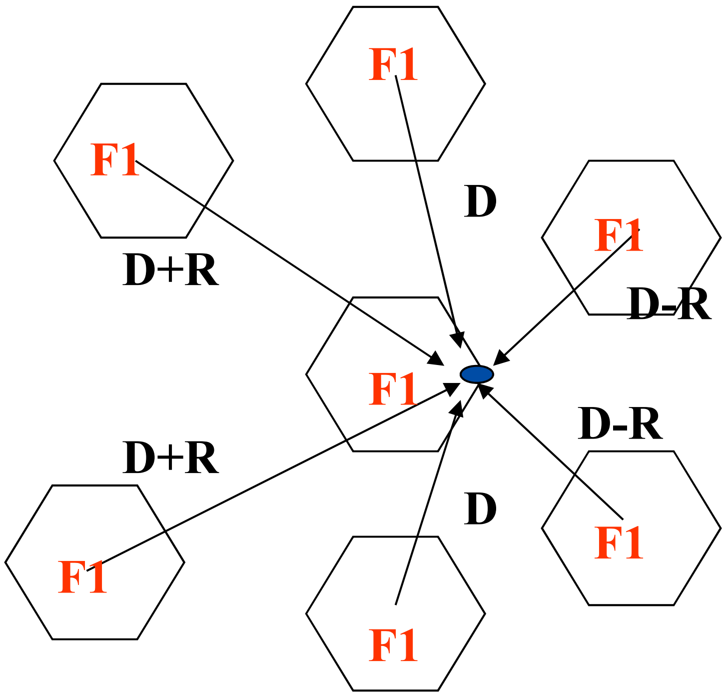
d_i : distance of ith interferer

Received power proportional to d_i^{-m} for $2 \le \boldsymbol{m} \le 4$

For homogeneous base stations and path loss experiment,

$$\frac{S}{I} = \frac{r^{-m}}{\sum_{i=1}^{n_0} d_i^{-m}} = \frac{\left(\frac{d}{r}\right)^m}{i_0} = \frac{\left(\sqrt{3N}\right)^m}{i_0}$$

Co-channel Interference



$$\frac{D}{R} = \sqrt{3N}$$

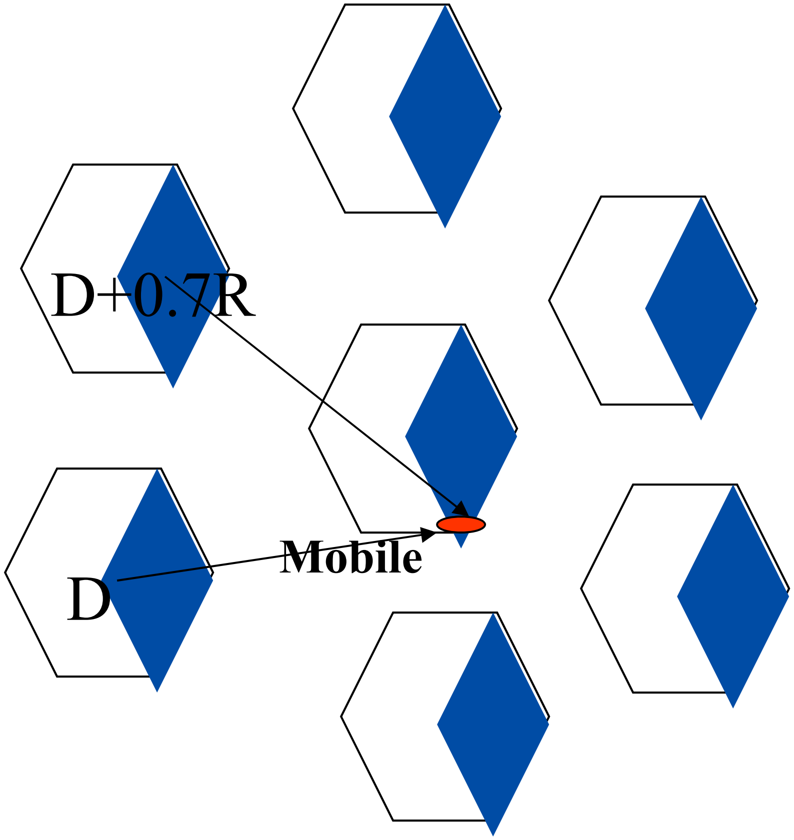
$$N = 7$$

$$\frac{D}{R} = 4.6$$

$$\Lambda = 17\, dB$$

$$\Lambda = \frac{1}{2} \frac{R^{-\gamma}}{(D+R)^{-\gamma} + D^{-\gamma} + (D-R)^{-\gamma}}$$

Interference: Sectored Cell



120^0 Sectored Cell

$$\frac{D}{R} = \sqrt{3N}$$

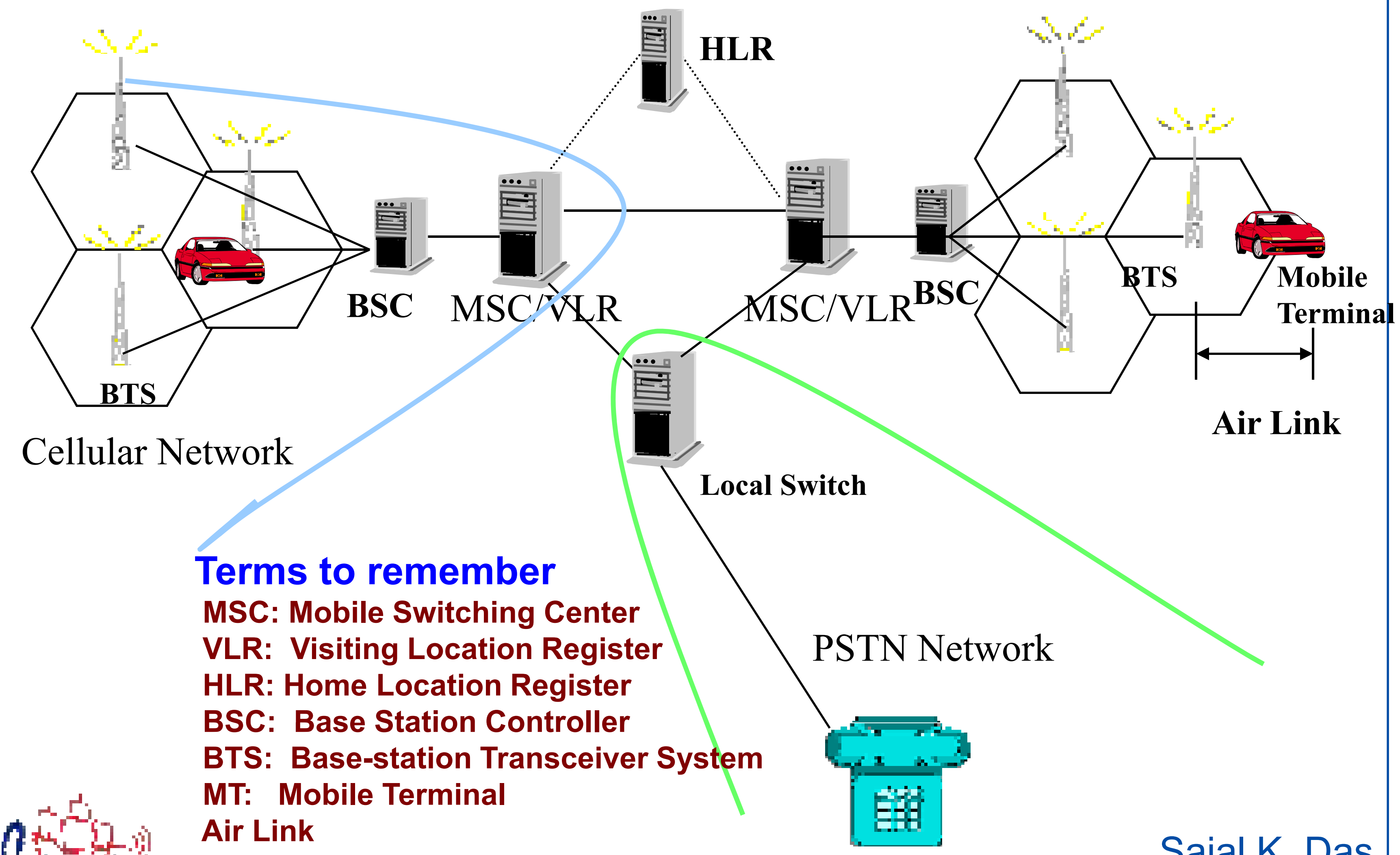
$$N = 7$$

$$\frac{D}{R} = 4.6$$

$$\Lambda = 24.5\, dB$$

$$\Lambda = \frac{R^{-\gamma}}{\left(D + 0.7R\right)^{-\gamma} + D^{-\gamma}}$$

Cellular Architecture



Terms to remember

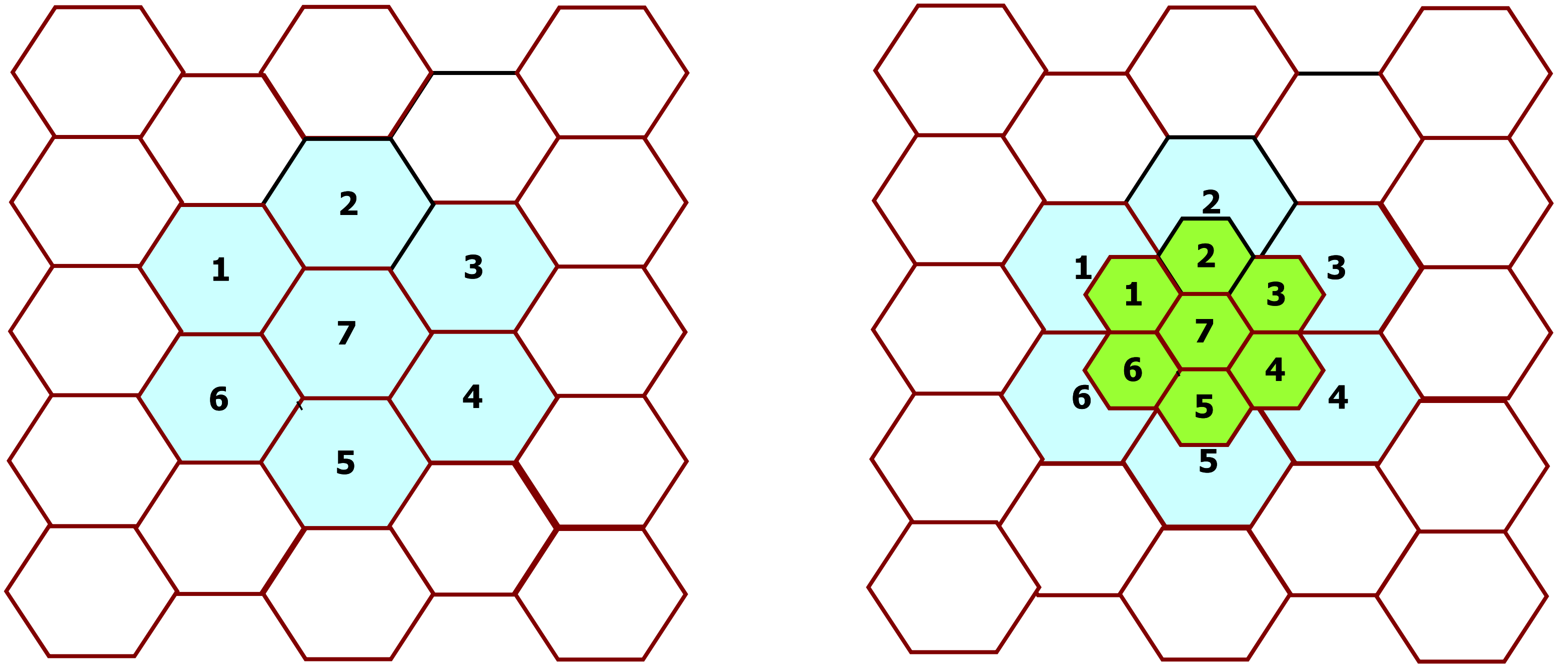
MSC: Mobile Switching Center
VLR: Visiting Location Register
HLR: Home Location Register
BSC: Base Station Controller
BTS: Base-station Transceiver System
MT: Mobile Terminal
Air Link

Capacity Improvement

- Network capacity (expressed by N) and interference conditions (expressed by C/I) are closely related
- Cell sectoring reduces interference by reducing the number of co-channel interferers each cell is exposed to. E.g., in 60 degrees sectored antenna has only 1 interferer as compared to 6 in omni-directional antennas. Cell sectoring also splits the channel sets into smaller groups, reducing *trunk efficiency*
- Cell splitting allows creation of smaller (micro, pico) cells, thus the same number of channels is used for smaller area. For the same probability of blocking, more users can be supported

Cell Splitting

- ❑ **Advantage**: more capacity, only local redesign of the system



- ❑ **Disadvantage**: more hand-offs, increased interference levels, more infrastructures

Cell Sizing

- To allow more capacity, cell sizes are scaled down
- Since C/I depends only on D/R, performance (interference level) is unaffected by the scaling
- Same number of channels can be used in a smaller area (larger user density), increase in the total number of concurrent users is proportional to α^{-2}, where α is scaling factor
- Smaller cells imply less transmitted power, smaller and lighter handset, but larger hand-off rate
- Cell size reduction leads to micro cells (e.g., shopping mall) and pico cells (e.g., building floor)
- Trade-off between bandwidth and coverage area – smaller range transceivers have higher bandwidths

Cell Sizing: Examples

Case 1:

Cell radius = 1 mile

Number of cells = 32

Number of channels = 336

Reuse factor N = 7

➡ 48 channels per cell

➡ 1536 concurrent calls

Case 2 (capacity quadrupled)

Cell radius = 0.5 mile ($\alpha = 0.5$)

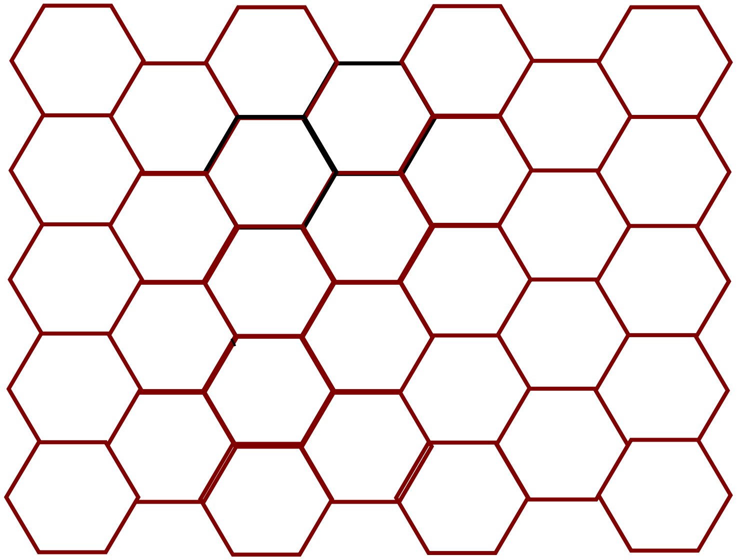
Number of cells = 128

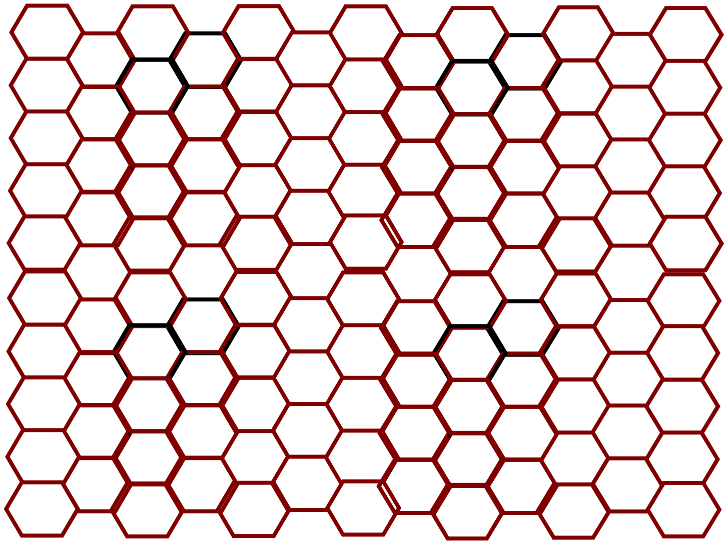
Number of channels = 336

Reuse factor N = 7

➡ 48 channels per cell

➡ 6144 concurrent calls





HW # 2

- Given a hexagonal geometry and shift parameters *i* and *j,* prove that the number of cells in a reuse pattern is given by

$$\mathbf{N = i^2 + i\,j + j^2}$$

- Enumerate possible values of N that will lead to feasible reuse patterns. Write a program to generate reuse patterns and identify co-channel cells with colors.

- For hexagonal geometry, prove that the co-channel reuse ratio is $\mathbf{D / R = \sqrt{3N}}$ where D is the distance between two co-channel cells and R is radius of a cell.

- From wireless communication standpoint, convince that

$$\mathbf{C / I \approx (D / R)^4 / 6}$$

HW # 2 (Cont’d)

- A total of 24 MHz bandwidth is allocated to a cellular system using 30 KHz full duplex channels. Let each phone generate 0.1 Erlang traffic.

  (a) Find # of channels in each cell for a 4-cell reuse pattern.

  (b) If each cell offers a capacity of 90% of perfect scheduling, find the # of users supported per cell using omni-directional and 120 degrees sectored antennas.

  (c) What is the blocking probability of the system in case (b) when the maximum # of users are available in user pool?

  (d) If each cell covers 5 square Km, how many subscribers can be supported in a 50 Km X 50 Km urban area for omni-directional and 120 degrees sectored antennas?

HW # 2 (Cont’d)

- A certain area is covered by a cellular radio system of 84 cells and a cluster size *N.* A total of 300 channels are available. Users are uniformly distributed over the area, and the offered traffic per user is 0.04 Erlang.

  Assume call blocking probability of 1%.

  For N = 4, 7, 12,

  (a) Determine the maximum carried traffic per cell,

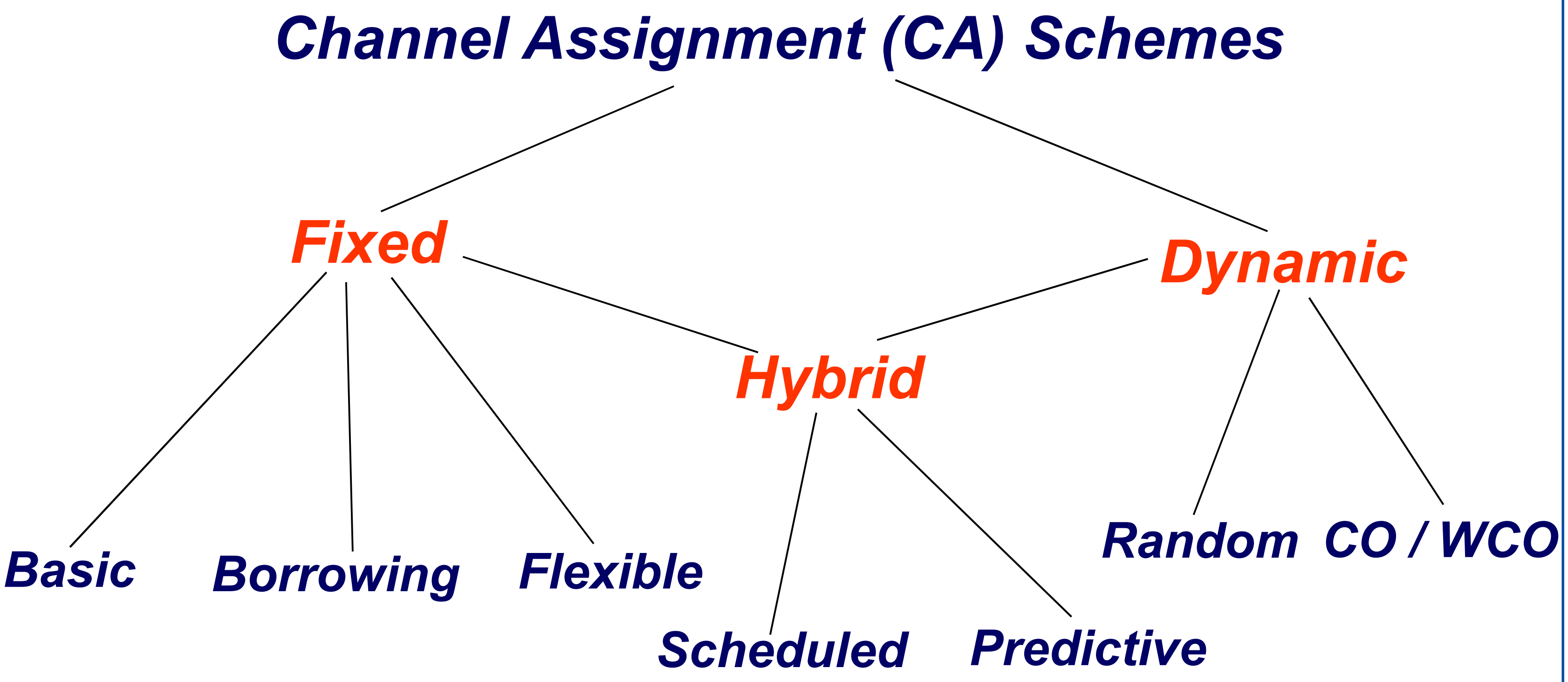
  (b) Determine the maximum number of users that can be served.

Lecture 3: Channel Assignment

- Fixed Channel Assignment (FCA)
- Channel Borrowing
- Dynamic Channel Assignment (DCA)
- Hybrid Schemes
- HW #3
- References

CA Schemes

- **Input:** Given a set of channels or frequencies (F) and a set of base stations (B) in the coverage area
- **Goal:** Determine an assignment of channel(s) to base stations such that frequency reuse is maximized



Fixed Assignment (FCA)

- Permanently assign a fixed set of channels to each cell and reuse them in the co-channel cells
- A user is assigned an unoccupied channel on demand, which is relinquished after the call is over
- If the number of calls exceeds the channel set for a cell, the excess calls are blocked
- Various graph coloring techniques can be used to maximize reuse of the available frequency channels
- Static channel assignment schemes perform well under heavy traffic conditions
- Does not solve hot spot (over-loaded cell) problem

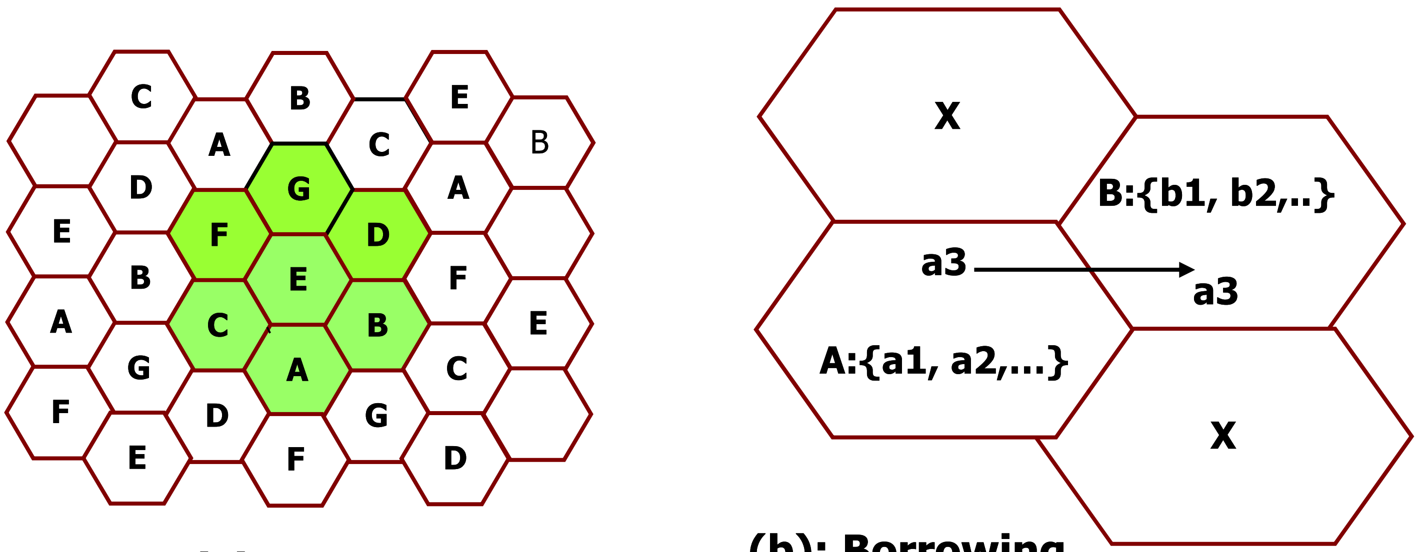
Variants of FCA

❑ Simple Borrowing

- A channel is borrowed from neighboring cell if no interference with existing calls

- Borrowed channel is locked in non-co-channel cells of borrower cell

- Channel locking ➔ performance suffers under heavy traffic conditions



(a): FCA **(b): Borrowing**

(a) **A - G denote different sets of channels permanently assigned to cells**

(b) **Channel a3 borrowed by B from A. Cells marked X are prohibited from using a3**

Variants of FCA

- Flexible Borrowing
  - Fixed channel set of a cell divided into two groups: One group for local use only, other group of channels for borrowing
  - Number of channels in each group determined a priori depending on traffic conditions
- Borrowing-with-channel-ordering
  - Extension of flexible borrowing, where the number of channels in both groups can vary dynamically depending on the traffic
  - Each channel is ordered -- the first channel has highest priority of being locally used and the last channel has highest priority of being borrowed. Ordering depends on traffic pattern
  - Released higher order channel is reallocated to ongoing call using lower order channel, to unlock borrowed channels

Dynamic Assignment (DCA)

- No cell has proprietary set of channels. Channels allocated to users on demand from a central pool based on a cost function
- Random DCA
  - Randomly assign available channel — poor channel utilization
- Channel Ordering (CO)
  - A cell can use any channel, but each has a different ordering. Select a channel with the highest priority for the cell
- Weighted Carrier Ordering (WCO)
  - Each cell develops “favorite” channels from past experience. Adapts faster to traffic changes than DCA-CO, but needs more time to search for the highest priority channel

Hybrid Assignment (HCA)

- A set of permanent (fixed) channels is allocated to each cell. For channel shortage in a cell, channels are assigned from a set of flexible channels according to a DCA strategy
- Flexible channels can be distributed among cells in a *scheduled* or *predictive* manner
- Scheduled distribution assumes knowledge of future changes in traffic distribution, while predictive scheme continuously monitors the traffic in each cell so that flexible channel reallocation can be done at any time

Comparison of CA Schemes

- Fixed Channel Assignment (FCA)
  - Not flexible, poor utilization
  - High blocking rate for non-uniform traffic
  - Low computational cost
  - Requires frequency planning
  - Not desirable in micro-cell architectures
- Dynamic Channel Assignment (DCA)
  - High utilization of channels
  - High computational complexity
  - Suitable for non-uniform traffic and micro-cell architectures
- Hybrid Channel Assignment (HCA)
  - Combination of FCA and DCA
  - Converges to FCA performance under heavy traffic

New DCA Algorithm

Goal: Given the available set of channels **F**, and the set of Base Stations **B** in the coverage area:

Find an assignment of a subset of channels to a mobile m_i in the coverage area of base station B_k such that the mobile and the base station can communicate with a tolerable interference on the channel(s).

$$m_i \rightarrow ch_{jk} \rightarrow B_k$$

Features:

- Maximize channel utilization
- Minimize interference
- Fast
- Adapt to the changes in the system

Flow Networks

- A flow network ***G_F* = (*V*, *E*)** is a directed graph, where ***V*** has two designated nodes: a source node ***s*** and a sink node ***t***. Each Edge in ***E*** associated with a cost ***c***, non-negative lower and upper capacity bounds ***l*** and ***u*** respectively.

- A flow ***f*** in ***G_F*** is a real-valued function

$$f : V \times V \rightarrow R$$

that satisfies the **Capacity**, **Skew Symmetry** and **Flow Conservation** constraints.

Dynamic Multi-Channel Assignment

- Construct a flow network that has vertices for
  - Each mobile that is active in the system
  - Each base station in the coverage area
  - Each channel supported by each base station
- Assign capacity and cost to each edge to reflect
  - Minimum and maximum channel demand by each mobile
  - Interference experienced by the mobile on downlink channel
  - Interference experienced by base station on uplink channel
  - Penalty for inter/intra cell handovers
- Run augmenting shortest paths on the residual network to handle call arrivals and reassignments

HW # 3

- Design a dynamic channel assignment algorithm using network flows.

- Read the first reference on the next page. Following the load balanced channel borrowing scheme presented in this paper, derive the probability of a cell being in a “hot” state. Also compute the threshold (*h*) that determines when a cell becomes hot.

- Read the second reference on the next page to understand thoroughly how the basic concept in the first paper can be generalized to borrow channels from any cells, even outside the reuse cluster. Go through all the mathematical steps.

Refs. on Channel Assignment

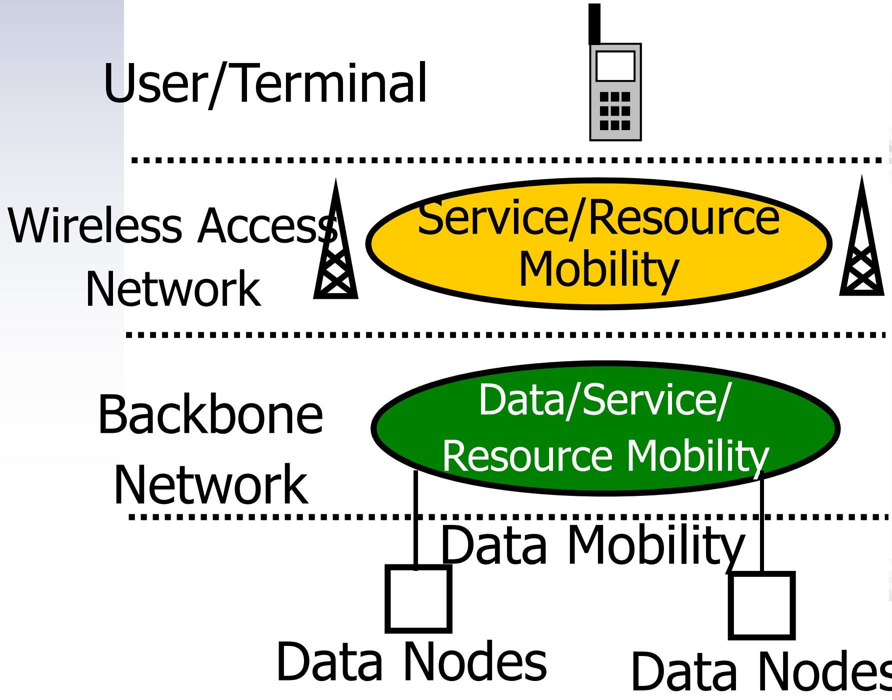
- S. K. Das, S. K. Sen, R. Jayaram, "A Dynamic Load Balancing Strategy for Channel Assignment Using Selective Borrowing in Cellular Mobile Environment," *ACM Wireless Networks*, Vol. 3, No. 5, pp. 333-347, 1997. (Also ACM Mobicom'96)
- S. K. Das, S. K. Sen, and R. Jayaram, "A Novel Load Balancing Scheme for Tele-Traffic Hot-spot Problem in Cellular Networks," *ACM Wireless Networks*, Vol. 4, No. 4, pp. 325-340, 1998. (Also Proc. IEEE ICDCS'97)
- S. K. Das, S. K. Sen, and R. Jayaram "D-LBSB: A Distributed Load Balancing Algorithm for Channel Assignment in Cellular Mobile Networks," *Journal of Interconnection Networks*, Vol. 1, No. 3, pp. 195-220, Dec 2000.
- S. De and S. K. Das, "Maximum Achievable Capacity Gain Through Traffic Load Balancing in Cellular Radio Networks: A Practical Perspective," *Proc. HiPC'01*, LNCS Vol. 2228, Springer, pp. 321-330, Dec 2001.
- Y. Zhang, S. K. Das, and X. Jia, "D-CAT: An Efficient Approach for Distributed Channel Allocation in Cellular Mobile Networks," *ACM Mobile Networks and Applications*, Vol. 9, No. 4, pp. 279-288, July 2004. (Also IEEE Globecom'01)
- B. S. Panda, M. Kumar and S. K. Das, "Optimal Schemes for Channel Assignment Problem in Wireless Networks Modeled as 2-dimensional Square Grids," *Proc of 6th Int'l Workshop on Distributed Computing* (IWDC) pp. 424-434, Dec 2004.
- O. Koyncu and S. K. Das, "Dynamic Channel Assignment Using Network Flows in Wireless Data Networks," *Journal of Microprocessors and Microsystems* (Special Issue on Resource Management in Wireless and Ad hoc Mobile Networks), Vol. 28, pp. 417-426, 2004. (Also Proc. ACM DIAL-M'98, IEEE VTC'99).

Outline

- **June 18:**
  - Wireless Mobile Communications – Fundamentals
  - Cellular Network Concepts and Channel Assignment
  - Mobility Management and Wireless Internet
  - Resource Management and Wireless QoS
- **June 19:**
  - Wireless Sensor Networks (WSNs) – Fundamentals
  - Pervasive Computing and Cyber-Physical Systems (CPS)
  - Energy-Efficient Algorithms and Protocols for WSNs
  - Security Solutions in WSNs
- **June 20:**
  - Smart Environments – Design and Modeling
  - Smart Healthcare – Middleware Services
  - Guidelines to Excellent Research
  - Mentoring and Value-Added Education

Mobile Computing Environment

- Combination of wired backbone networks and dynamically changing wireless networks
- Wireless *base stations* (BS) linked to *mobile switching center* (MSC), that are linked through wired networks such as PSTN or Internet.



User/Terminal

Wireless Access Network

Service/Resource Mobility

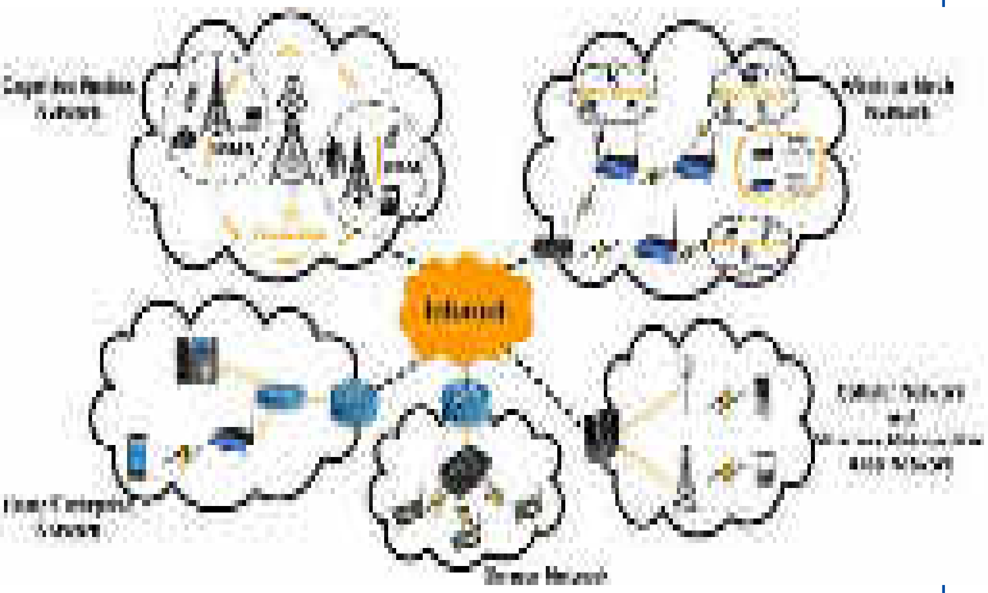
Backbone Network

Data/Service/ Resource Mobility

Data Mobility

Data Nodes

Data Nodes



Characteristics of Mobile Networks

- Radio Resource scarcity
  - Limited wireless bandwidth: Kbps–Mbps (Wired: Mbps–Gbps)
- Unreliable wireless links
  - Varying channel conditions (multi-path fading, shadowing)
  - High bit-error-rate (BER): 10^{-4} – 10^{-3} (Wired: million times smaller)
  - Frequent disconnection (Intermittent connectivity)
- Continuously evolving network topology
- User Mobility — paradigm shift in computing
- Uncertain availability of resources & services
- Inherently less secured
- Energy (battery power) limited

Challenges of Mobile Computing

- Coping with Uncertainty in Wireless Networks
  - Uncertainty in time varying wireless links, user mobility, topology, routing, resource demands, traffic loads, application quality of service (QoS)
- Seamless Roaming in Heterogeneous Access (GSM, CDMA, IEEE 802.11 Wireless LAN)
- User or Device Location / Mobility Management
- Dynamic Topology Management and Routing
- Mobile Data Management and Services
- Wireless Internet: Micro-Mobility and Macro-Mobility

Lecture 4: Mobility Management

- Hand-off
- Location Management
- Update (Registration) and Paging Schemes
- Next Generation Mobility

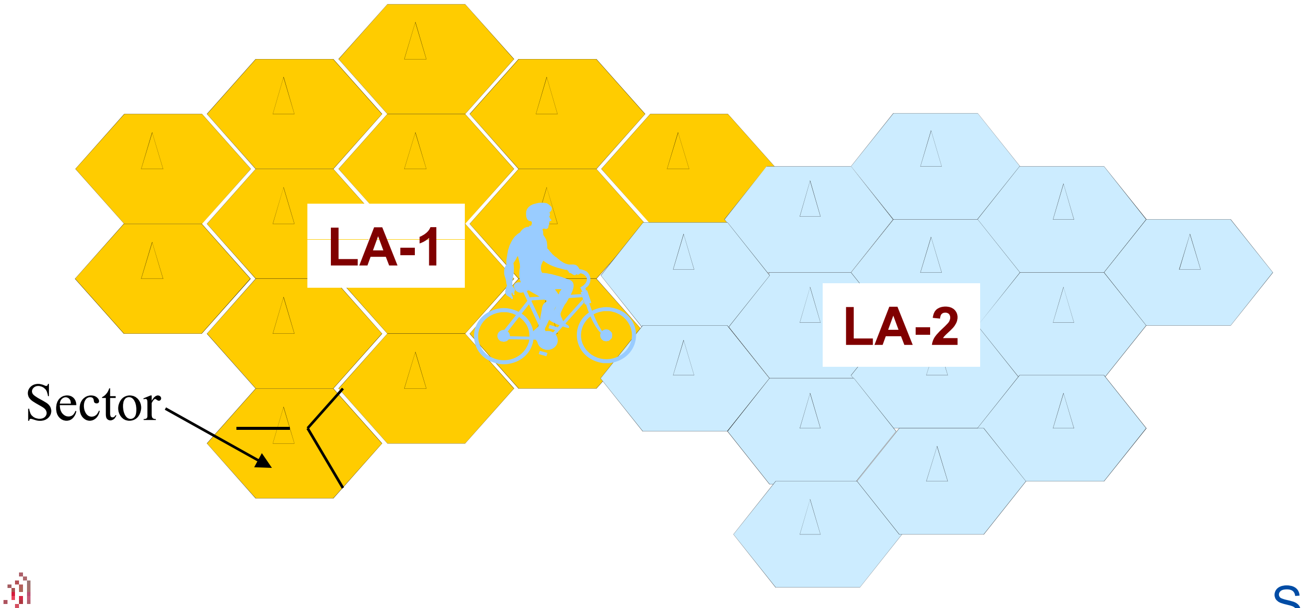
Types of Mobility

- Terminal (Device) Mobility
  - Ability of the network to route calls to mobile terminals regardless of the point of attachment
- Personal Mobility
  - Ability to use the same terminal by different users at the same time through different addresses
  - Universal Personal Telephone Number (UPT)
- Service /Session Mobility
  - Allows users to roam beyond own networks
  - Ability to move the complete set of services from one network to another

Mobility Management

Mobility is a new dimension – paradigm shift in computing

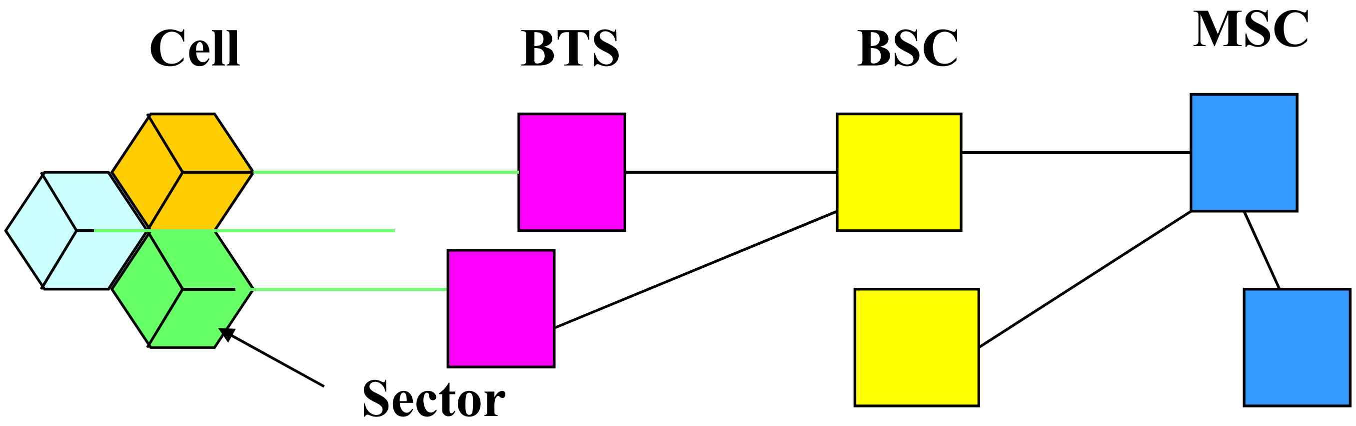
- In-session mobility management
  - Move during an active call
  - Hand-off management
- Out-of-session mobility management
  - Move in standby mode
  - Location management



Sajal K. Das

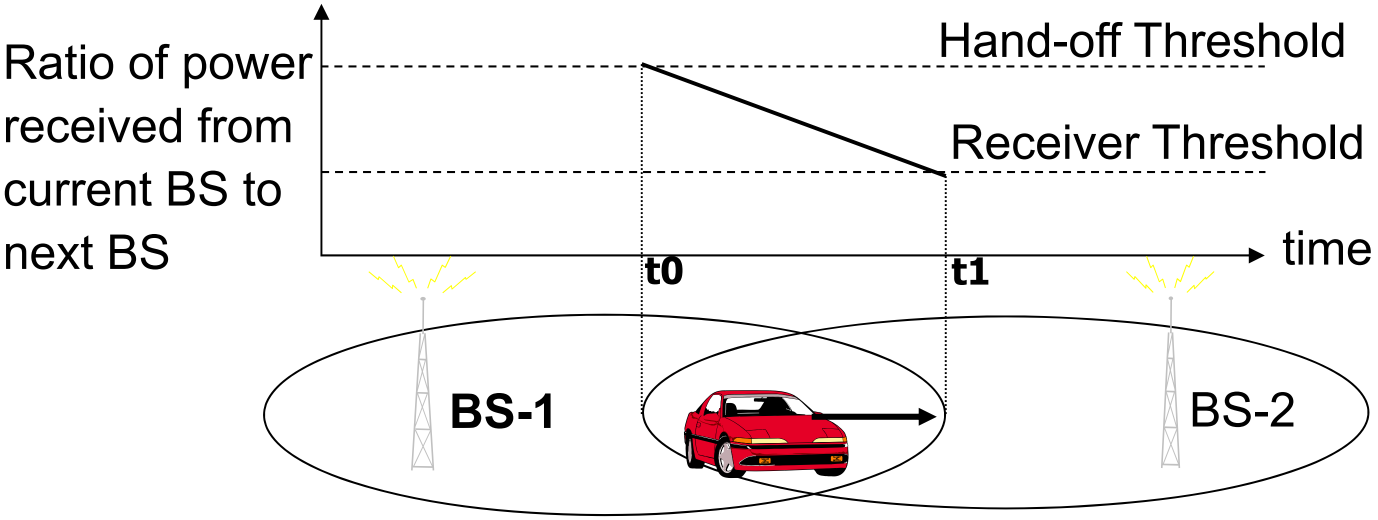
Cellular Mobility

- Micro-Mobility
  - Mobility between Sectors: Hand-off
  - Mobility between BTSs : Hand-off
  - Mobility between BSCs : Inter BSC Hand-off
- Macro-Mobility
  - Mobility between MSCs : Inter MSC Hand-off
- Global Mobility (IP Mobility)
  - Mobility between different administrative domain



Hand-off Problem

- Switching from one channel to another during communication
- Induced by Received Signal Strength (RSS), Signal-to-Noise Ratio (SNR) and Bit Error Rate (BER)
- RSS attenuates due to distance from BS, slow fading (shadow or lognormal fading), and fast fading (Raleigh fading)
- Hand-off triggered by BS or mobile station

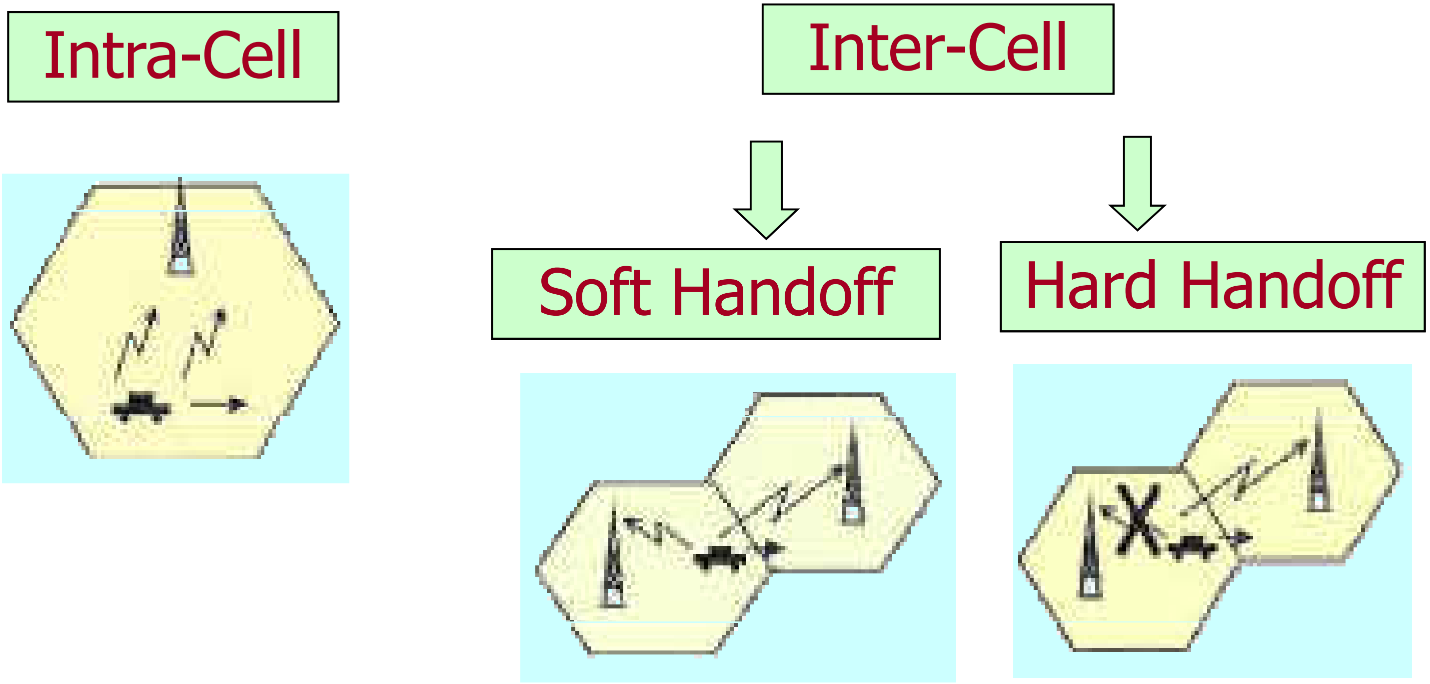


Hand-off and Receiver thresholds
Linear motion assumed from BS-1 to BS-2
Hand-off must occur in [t0, t1]

Hand-off Policies

- BS handles hand-off requests in same manner as originating calls
  - Disadvantage: Ignores that an ongoing call has higher priority for a new channel than originating calls
  - Solution: Prioritize hand-off channel assignment at the expense of tolerable increase in call blocking probability
- Guard channel concepts
  - Reserve some channels exclusively for hand-offs. Remaining channels shared equally between hand-offs and originating calls
  - In FCA, each cell has a set of guard channels. In DCA, channels are assigned during hand-off from a central pool
  - Disadvantages:
    - Penalty in reduction of total carried traffic since fewer channels are available for originating calls. Partially solution is to queue up blocked originating calls
    - Inefficient spectrum utilization – estimate optimum number of guard channels. Also call termination probability strictly not zero

Handoff Types



Intra-Cell

Inter-Cell

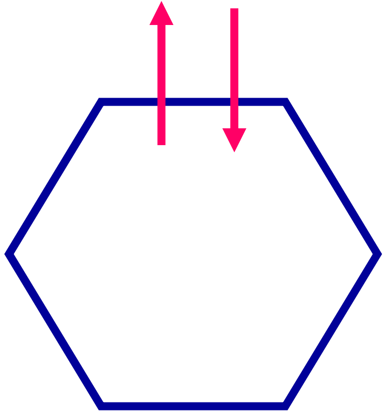
Soft Handoff

Hard Handoff

Mobility Models:

- Fluid Flow Model
- Random Walk Model
- Gravity Model

Mobility Rate in a Cell



Location Management

- Problem: Tracking a mobile station to route incoming call requests within an allowable time constraint
- Why Important?
  - To support user mobility (in stand by mode)
  - While enjoying the freedom of being mobile, the user creates an uncertainty about the exact location of the mobile station
  - Unless controlled, uncertainty may grow without bound
- Location Management Protocols: Two Components

Device centric

Location Update (Registration)

Network centric

Call Delivery (Paging)

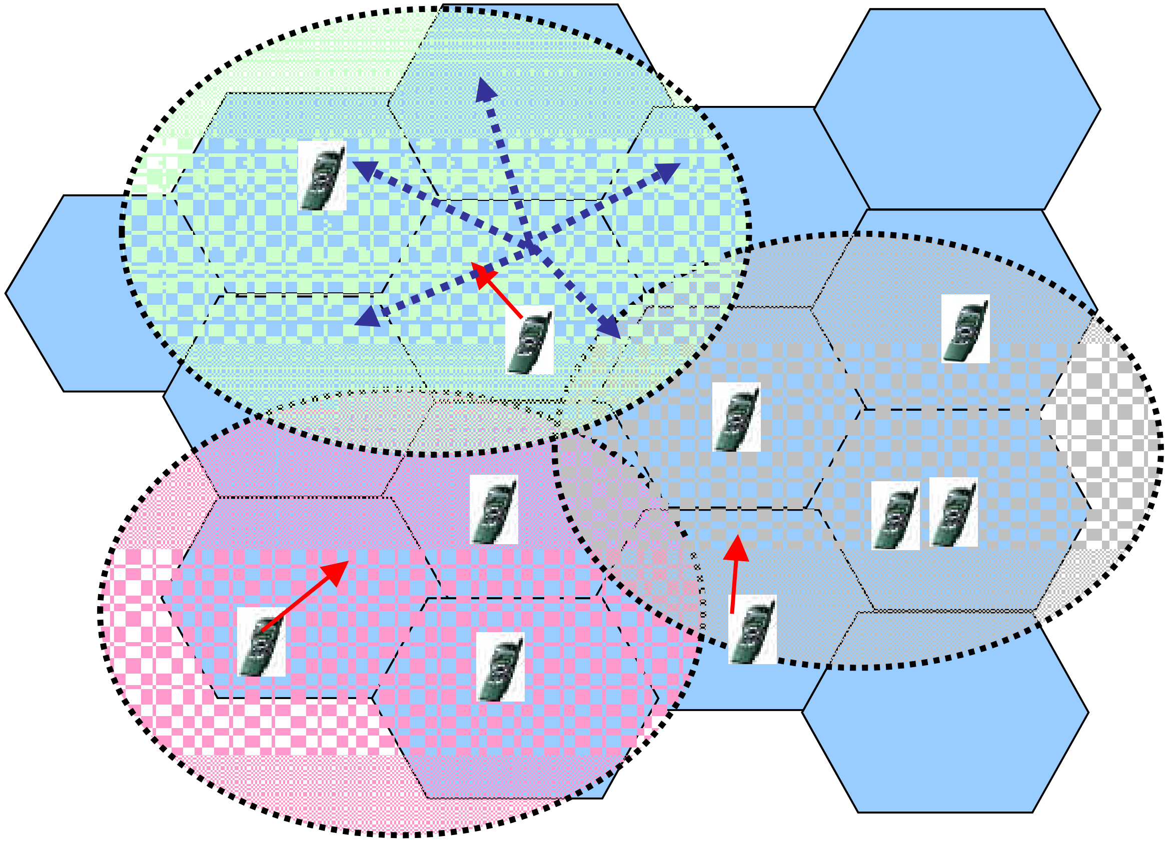
Nature of Location Information

- **Geometric**
  - Spatial: in 3D or 2D coordinates
  - GPS data for example
  - Pre-determined granularity
  - Reporting by dead-reckoning
- **Symbolic**
  - Usually a Cell-ID
  - Registration in Cellular/PCS network
  - Granularity and hierarchical structures
  - Reporting triggered by a threshold

Location Tracking Fundamentals

Location Update/ Registration: Mobile tells system "I'm here"

Paging/ System Search (when new session arrives): System searches for mobile with "where are you?"



- Management scheme is Global
- Does not learn from/exploit individual user mobility patterns
- Searching all cells of a single registration area is often very wasteful

Cost Components

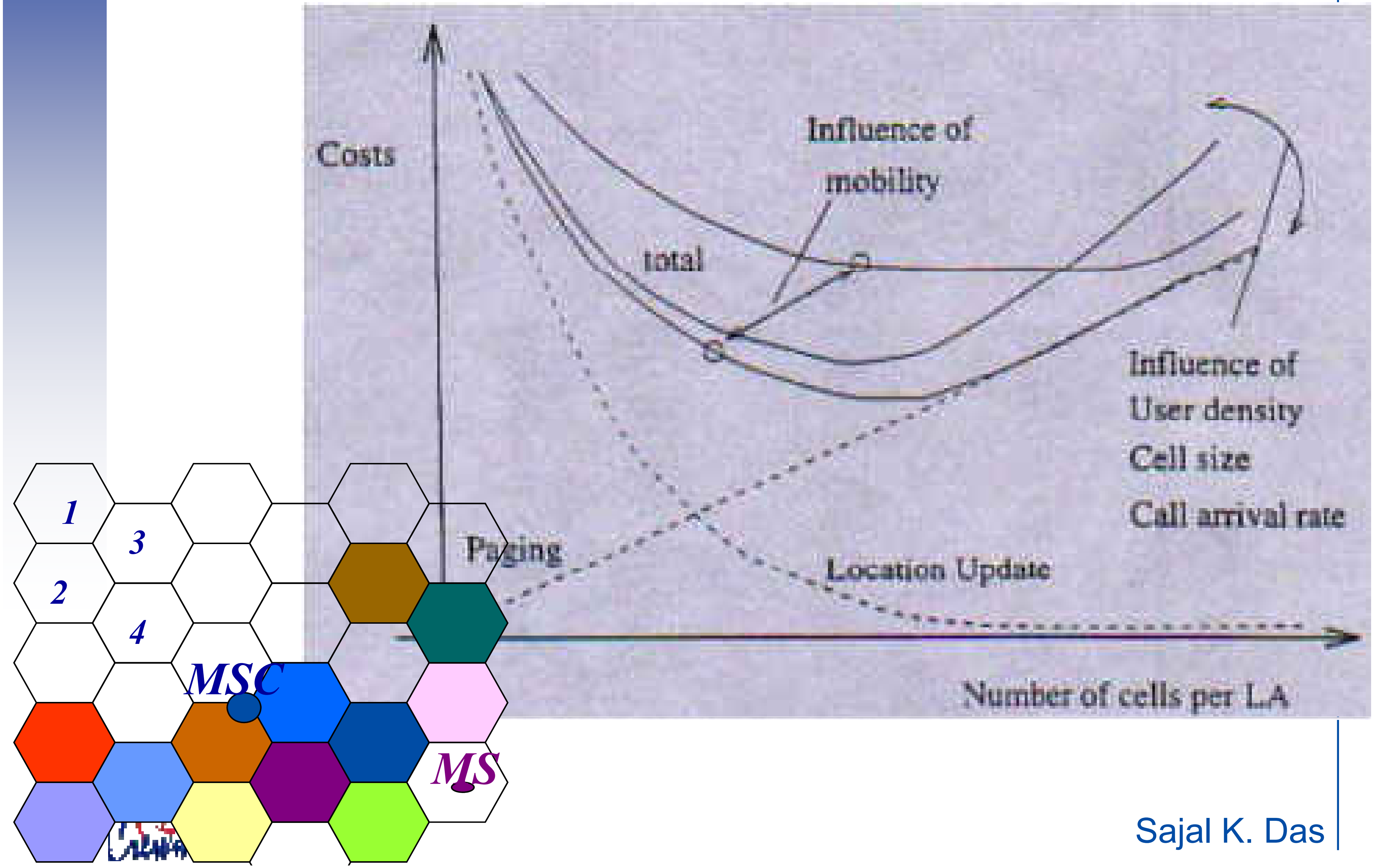
- Paging: The network polls the mobile terminal in cells by broadcasting the terminal's id and waiting for a response
- Update (registration): Mobile terminal updates its current location in the network
- Paging cost is proportional to:
  - Number of calls arrived
  - Number of cells paged for each call
- Update cost is proportional to:
  - Frequency of updates

Too Many Location Updates ⇨ **Low Paging Costs**
High Update Costs

Too Few Location Updates ⇨ **High Paging Costs**
Low Update Costs

Cost Trade-off

Update and paging costs are complementary but inter-dependent



Practical Solution

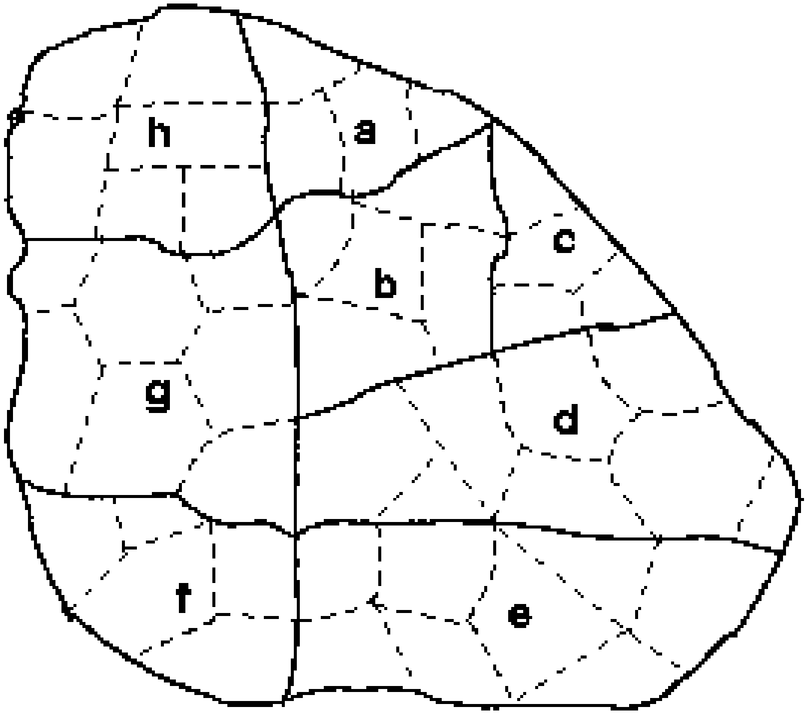
- Update mobile's location selectively from time to time to control uncertainty at a reasonable cost

  ➔ trade-off between update and paging

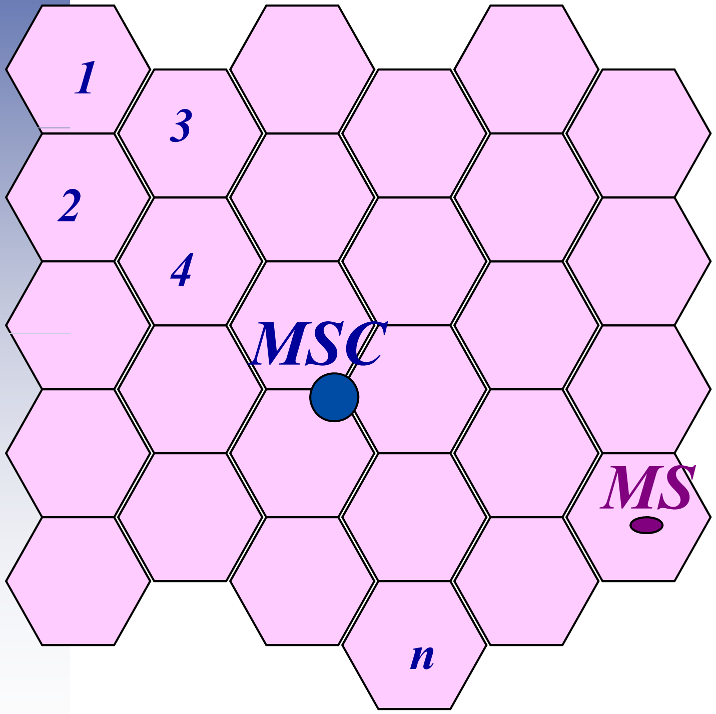
- Observation
  - A problem oriented towards personal mobility, not group mobility
  - Update and paging involve complementary cost components but not necessarily independent

Static Update Strategy

- Zone based
  - Common deployment (IS-41, IS-54B, IS-95, and GSM)
  - Group cells into Location Areas (LA)
  - Coarse granularity
  - Update at new LA
  - Global mobility model for all users



Single Location Area



- Assume single location Area (LA)
- *n* = 100 cells (BS's) under MSC
- MSC receives 100K calls
- 50% are terminating mobile calls

How many paging messages?

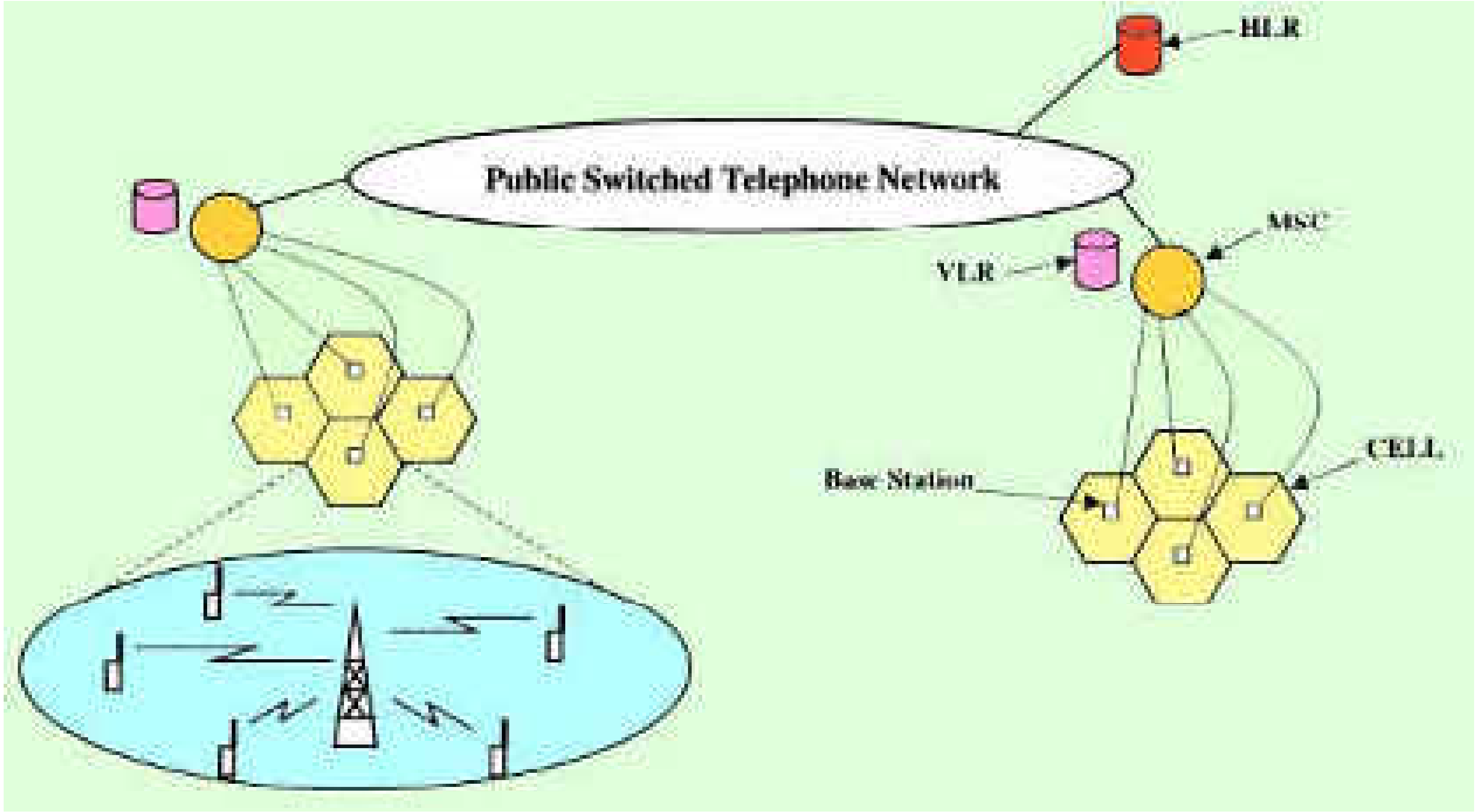
Total Paging Messages / cell
= $100X10^3X0.5X100$ = $5X10^6$

Location update messages = 0

MSC can find out the mobile within its LA without updating the changes for mobile movement from one cell to another

Location update message per cell proportional to average # of changes of cell per user

Paging in 2G Mobile Architecture

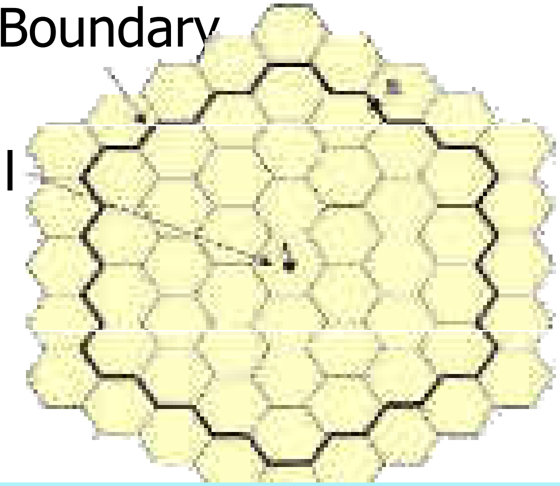


- ☐ HLR (Home Location Register): Database to route calls to the mobile stations; Stores IMSI (International Mobile Subscriber's identity), current VLR address

- ☐ VLR (Visitor Location Register): Contains current location of the mobile station; One VLR is associated with one MSC

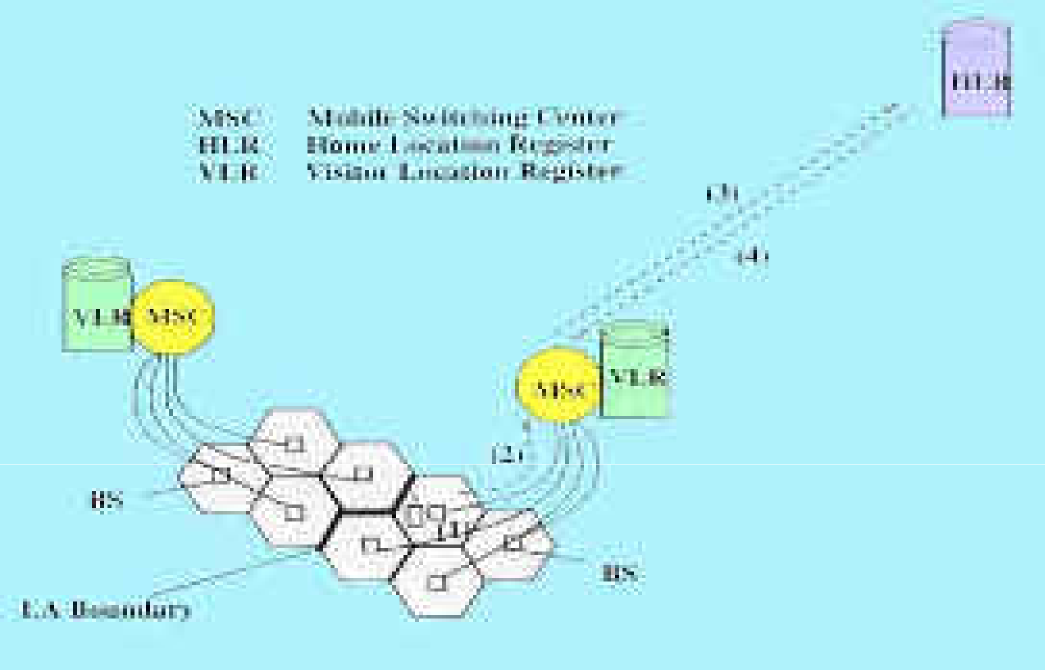
Location Registration in IS-41 System

- Location Area (GSM) = Registration Area (IS-41)

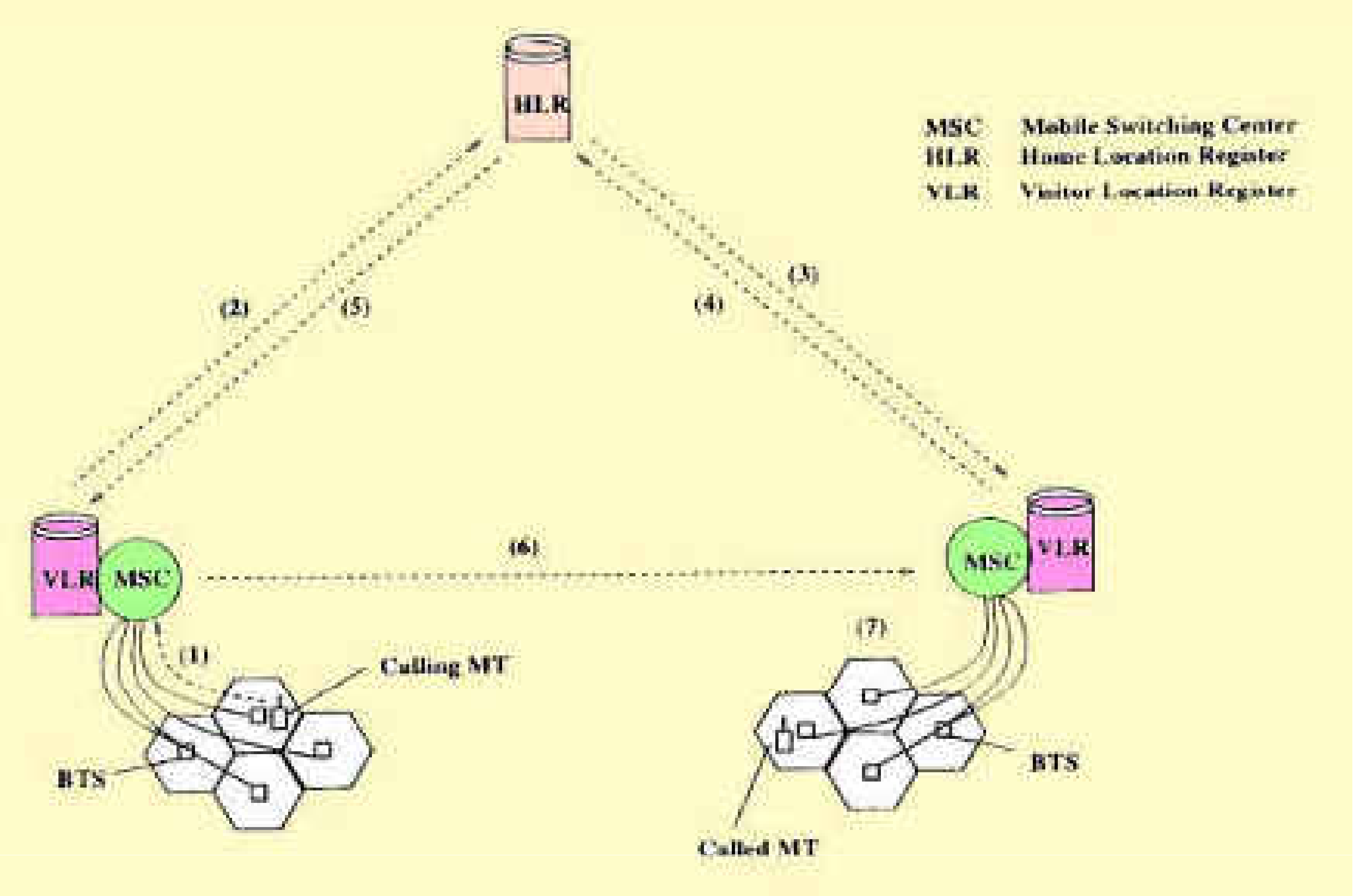


Registration Area Boundary

Center Cell



Call Delivery/Paging in IS-41



Terminal Paging Strategies

- Blanket polling
  - Polls all cells within current LA simultaneously
- Cluster paging / Selective paging
  - Selects next set of probable cells at each step
  - Follows omni-directional tiers around the last known cell
  - Polls the tiers in sequence until success
- Rank paging
  - Ranks search space by decreasing residence probability
  - Needs residence probability distribution for optimal solution
  - Polls sequentially under no time constraint
  - May determine the polling order by dynamic programming

Terminal Paging

- Need to know residence probability distribution
- Worst adversary? uniform distribution
- Rank search space by decreasing probability
- No time constraint? Poll sequentially
- Time constraint? Use dynamic programming
- Conditional or unconditional probability?
- How does one know the distribution?

Paging With No Update

- Optimal if residence probability distribution is known
- Ranking of the search space is needed
- Uniform distribution is the worst case scenario
- No time constraint
  - Polls cells sequentially in decreasing order of probability
- Constraint on maximum allowable delay
  - Dynamic programming solution in discrete case

Paging with “Position” Update

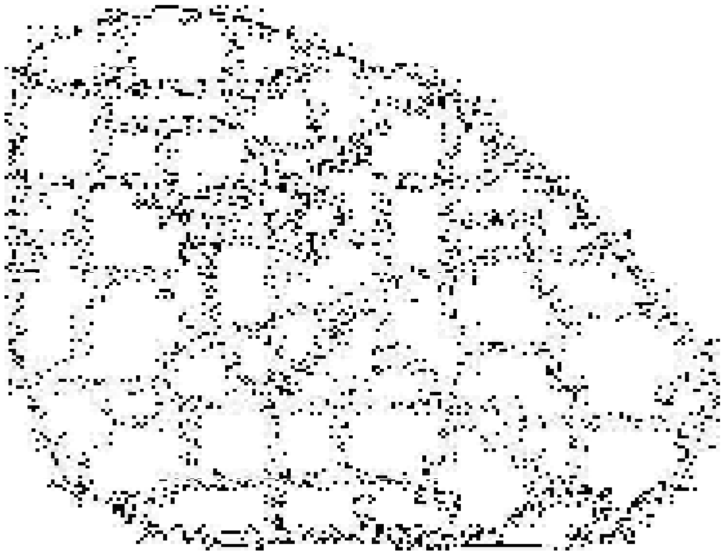
- Problem complexity
  - Location uncertainty is the real adversary
  - Optimal solution for restricted mobility models

- Cluster paging / Selective paging
  - Partly sequential
  - Search tier by tier around the last known cell
  - Select next set of probable cells at each step
  - Keep polling until success or timeout

Paging with Location Update

- Optimality issues
  - *Uncertainty*, not speed or velocity, is a key factor
  - Does not remain a stationary optimization problem
  - Optimal paging issues resolved only for restricted mobility models
- Selective paging
  - Partly sequential
  - Select a set of highly probable cells at each step
  - Proceed conditionally based on outcome of last step
  - Follow tiers of cells around the last known position

Dynamic Update Strategies



- Distance based
  - Distance threshold
  - Omni-directional
  - Implementation overhead (IS-95)
- Movement based
  - Count cell-crossing
  - Over-estimate
- Time based
  - Periodic, but optimal period depends on mobility model
  - Easy to implement (IS-95)
  - Inefficient when stagnant

A Predictive Framework for Mobility Management in Cellular Networks

A. Bhattacharya and S. K. Das, "LeZi-Update: An Information-Theoretic Approach to Track Mobile Users in PCS Networks," *ACM Wireless Networks*, Vol. 8, No. 2-3, pp. 121-135, Mar-May 2002. (ACM Mobicom'99 Best Paper Award)

Prediction: A Swiss Army Knife?

- Location management
  - Improvement on paging cost
  - Improvement on update cost (why?)

- Mobility support for real-time multimedia
  - Video conferencing / streaming
  - Early channel reservation / Mobile RSVP

- Location-aware computing
  - Smart home/office (follow-me applications)
  - Indoor/outdoor tracking (energy saver)
  - Information dissemination (travel info, tour guide)

Personal Mobility Management

- Inter-operability of heterogeneous networks
  - Indoor systems (IEEE 802.11, Bluetooth, Active badges)
  - Campus-wide LANs
  - Wide-area systems (Cellular/PCS based WAN)
  - Satellite systems (Satellite phones/routers, GPS)
- Service expansion
  - Real-time audio/video (QoS support)
  - Data services (including Internet applications)
  - Location / context-aware services
- Location tracking (update + paging)
  - Multiple devices as and when appropriate
  - Context of space and time
  - Wide range of granularity

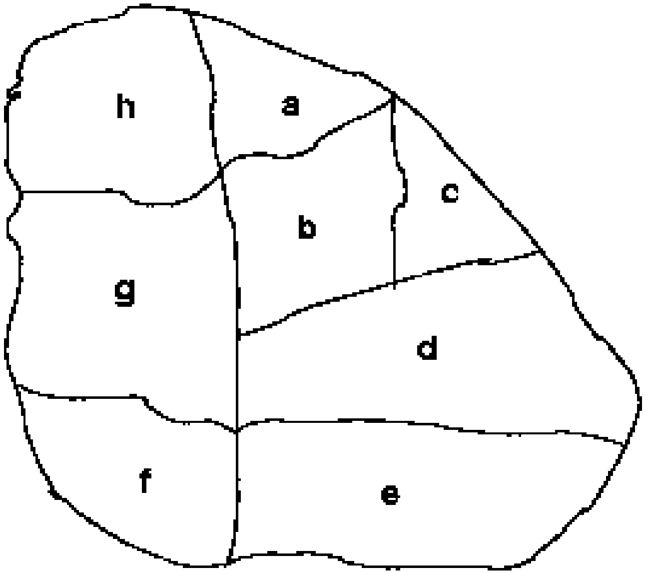
Motivation of Our Work

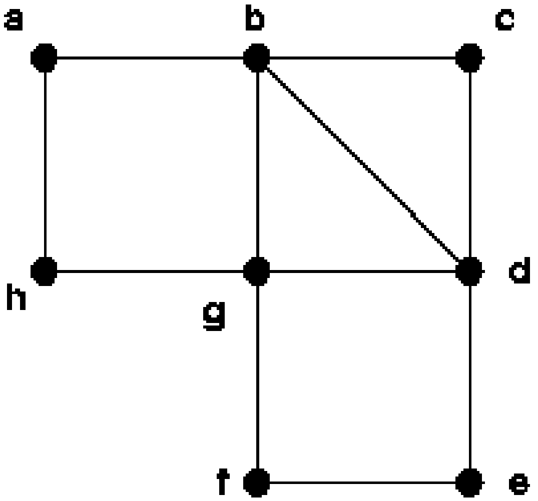
- What was missing?
  - Location prediction was never the goal before
  - No attempts made to characterize complexity
  - Different mobility models: no clear consensus
  - Directional aspect of motion ignored

- A few clues
  - Consider location uncertainty rather than distance
  - Consider symbolic capture of information (Cell-ID)
  - Characterize information /complexity
  - Use a good compressor as a good predictor

Model for a Cellular Network

- Cell geometry
  - Irregular shapes
  - Not hexagonal or square
  - Not arranged in a grid
- Connected graph
  - General representation
  - Nodes represent cells
  - Edges represent cell adjacency





Sajal K. Das

User Movement History

	a.m.			p.m.						
Time	11:04	11:32	11:57	3:18	4:12	4:52	5:13	6:11	6:33	6:54
Cross	a-b	b-a	a-b	b-a	a-b	b-c	c-d	d-c	c-b	b-a

Thresholds	**Update sequence**
Time (T = 1 hr)	aaabbbbacdaaa…
Movement (M=1)	abababcdcba…
Time & Movement (T = 1 hr, M = 1)	aaababbbbbaabccddcbaaaa…

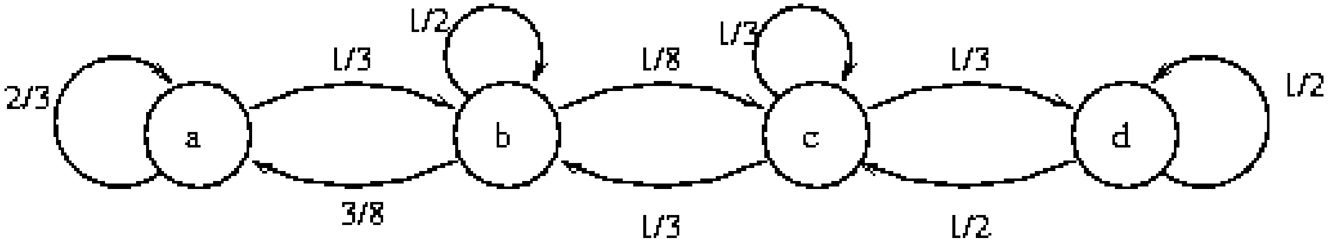
Context Model for Mobility

Movement history: a a a b a b b b b b a a b c c d d c b a a a a ….

- Order-(-1) (Ignorant) model
  - All locations are equiprobable
  - (1/8, 1/8, 1/8, 1/8, 1/8, 1/8, 1/8, 1/8)

- Order-0 (Steady-state) model
  - Location probabilities proportional to frequency of visits
  - (10/23, 8/23, 3/23, 2/23, 0, 0, 0, 0)

- Order-1 (Markov) model
  - One-step transition probabilities proportional to frequency of transitions
  - (9/22, 4/11, 3/22, 1/11, 0, 0, 0, 0)



Context Model for Mobility (Contd.)

Movement history:

a a a b a b b b b b a a b c c d d c b a a a a …

- Order-0 contexts:

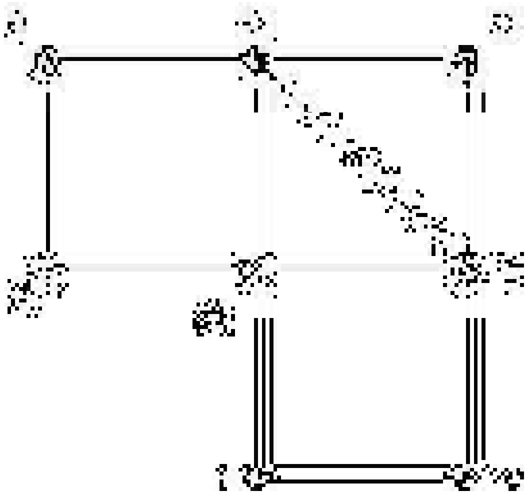
  a(10), b(8), c(3), d(2)

- Order-1 contexts:

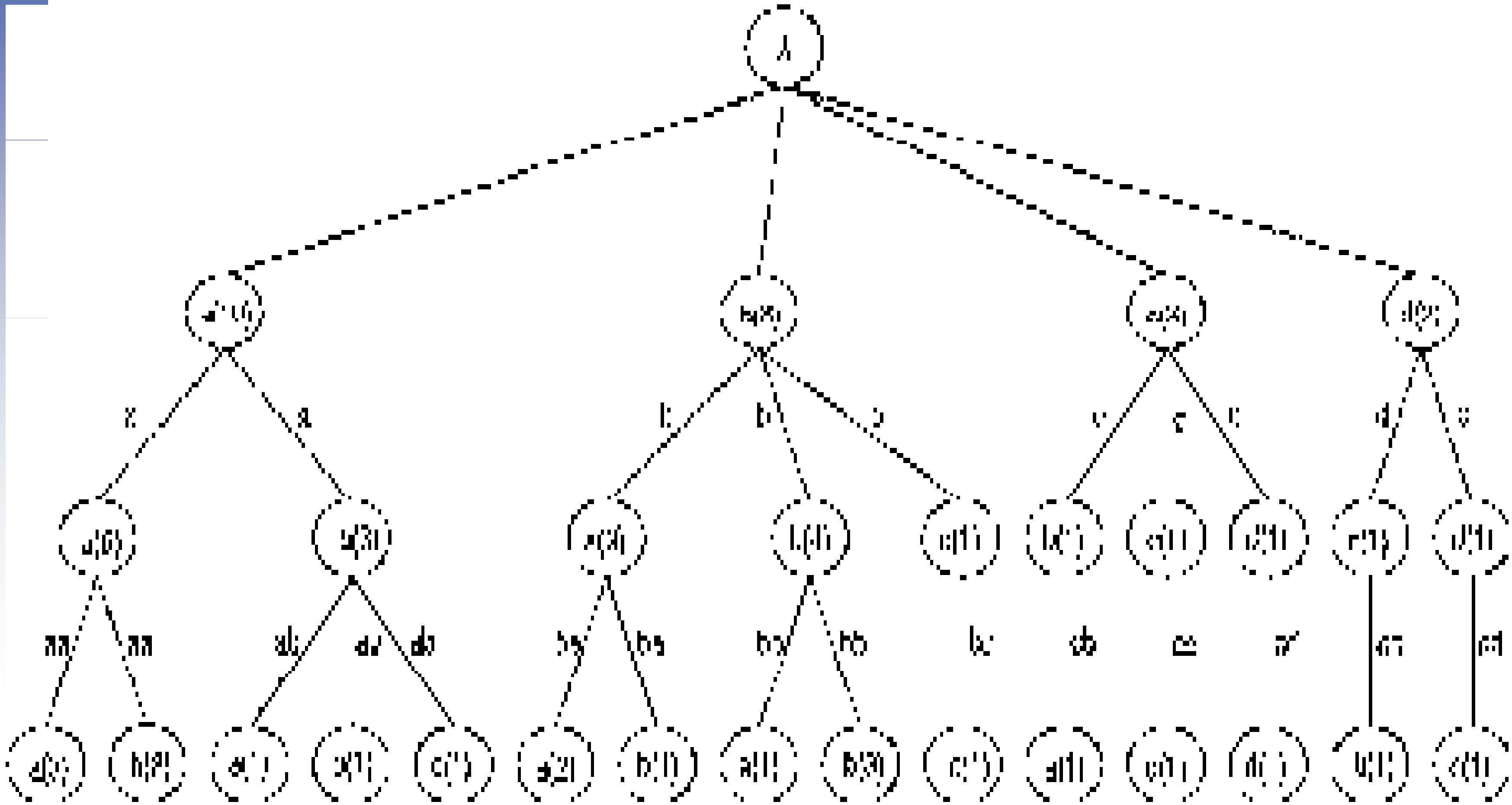
  a|a(6), b|a(3), a|b(3), b|b(4), c|b(1),
  b|c(1), c|c(1), d|c(1), c|d(1), d|d(1)

- Order-2 contexts:

  a|aa(3), b|aa(2), a|ab(1), b|ab(1), c|ab(1),
  a|ba(2), b|ba(1), a|bb(1), b|bb(1), c|bc(1),
  a|cb(1), d|cc(1), d|cd(1), b|dc(1), c|dd(1)



Context Trie for Orders 0, 1 and 2



LeZi-Update: A Universal Scheme

- A framework for route updates
  - Trips are planned in terms of routes
  - Routes are taken with stationary probabilities
  - Update message contains the path (context) since last update
  - Use Lempel-Ziv (LZ78) family of incremental parsing algorithm
  - Encode (*compress*) at mobile, decode (*decompress*) at MSC
- Advantages
  - Learns individual subscriber's mobility profile
  - Dictionary-based fast algorithm
  - Power of a finite-state model with a state-space that adapts
  - Efficient in reducing update messaging
  - Efficient prediction of location and direction of movement

A “Path” Update Alternative

- No need to update on known paths
- Uses “(known path-id, cell-id)” pair as update message

	a.m.			p.m.						
Time	11:04	11:32	11:57	3:18	4:12	4:52	5:13	6:11	6:33	6:54
Cross	a-b	b-a	a-b	b-a	a-b	b-c	c-d	d-c	c-b	b-a

Thresholds	**Update triggers**	**LeZi-update sequence**
Time (T=1 hr)	aaabbbbacdaaa…	a,aa,b,bb,ba,c,d,aaa…
Move (M=1)	abababcdcba…	a,b,ab,abc,d,c,ba…
Time & Move (T=1 hr, M=1)	aaababbbbbaabccddcbaaaa…	a,aa,b,ab,bb,bba,abc,c,d,dc,ba,aaa…

The LeZi-Update Algorithm

- LZ78 based incremental parsing [Ziv and Lempel, ToIT '78]
- Encode (compress) at mobile, decode (uncompress) at MSC

Procedure Encoder

```
initialize dictionary := empty
initialize phrase w := null
loop
    wait for next symbol v
    if (w.v in dictionary)
      w := w.v
    else
      encode <index(w),v>
      add w.v to dictionary
      w := null
    endif
forever
```

Procedure Decoder

```
initialize dictionary := empty
loop
    wait for next codeword <i,s>
    decode
      phrase := entry[i].s
    add phrase to dictionary
    increment frequency
        for every prefix
        of phrase
forever
```

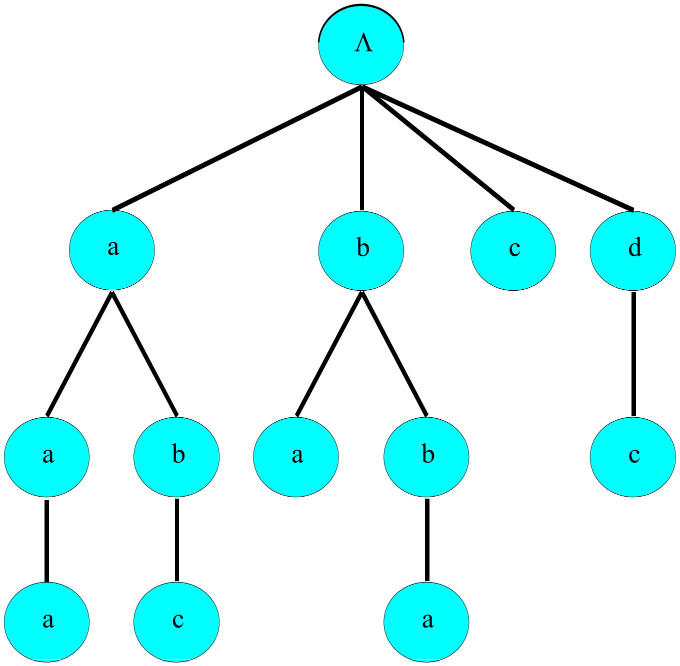
Example of Encoding

a, a a, b, a b, b b, b b a, a b c, c, d, d c, b a, a a a, …

(0,a)(1,a) (0,b) (1,b) (3,b) (5,a) (4,c) (0,c) (0,d)(9,c)(3,a) (2,a) …

Procedure Encoder

```
initialize dictionary := empty
initialize phrase w := null
loop
    wait for next symbol v
    if (w.v in dictionary)
      w := w.v
    else
      encode <index(w),v>
      add w.v to dictionary
      w := null
    endif
forever
```



Address	Phrase
0	Λ
1	a
2	a a
3	b
4	a b
5	b b
6	b b a
7	a b c
8	c
9	d
10	d c
11	b a
12	a a a

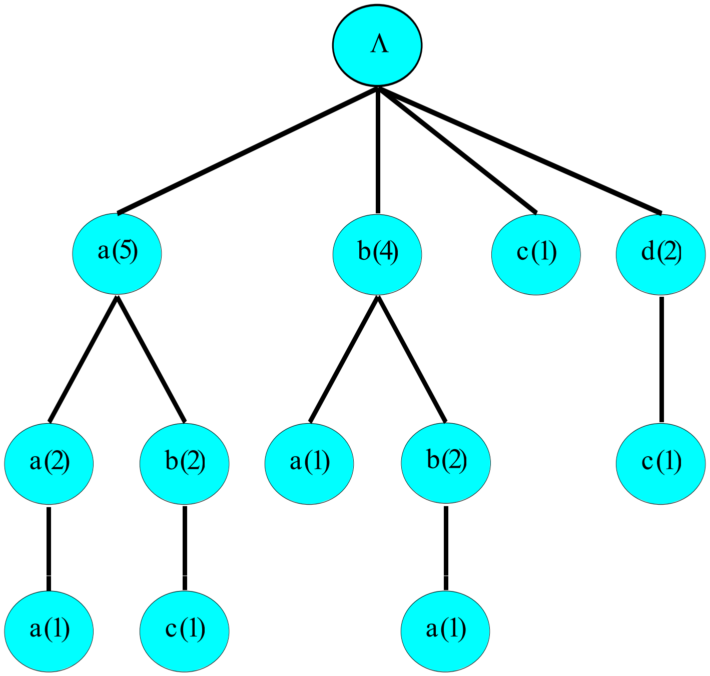
Example of Decoding

(0,a)(1,a) (0,b) (1,b) (3,b) (5,a) (4,c) (0,c) (0,d)(9,c)(3,a) (2,a) …

a, a a, b, a b, b b, b b a, a b c, c, d, d c, b a, a a a, …

Procedure Decoder

```
initialize dictionary := empty
loop
    wait for next codeword
    <i,s>
    decode
      phrase := entry[i].s
    add phrase to dictionary
    increment frequency
        for every prefix
        of phrase
forever
```



Address	Phrase
0	Λ
1	a (5)
2	a a (2)
3	b (4)
4	a b (2)
5	b b (2)
6	b b a (1)
7	a b c (1)
8	c (1)
9	d (2)
10	d c (1)
11	b a (1)
12	a a a (1)

Speeding up Dictionary Building

- Hard to capture contexts which cross phrase boundaries
- Suffixes of parsed phrases can be easily extracted

Procedure Encoder

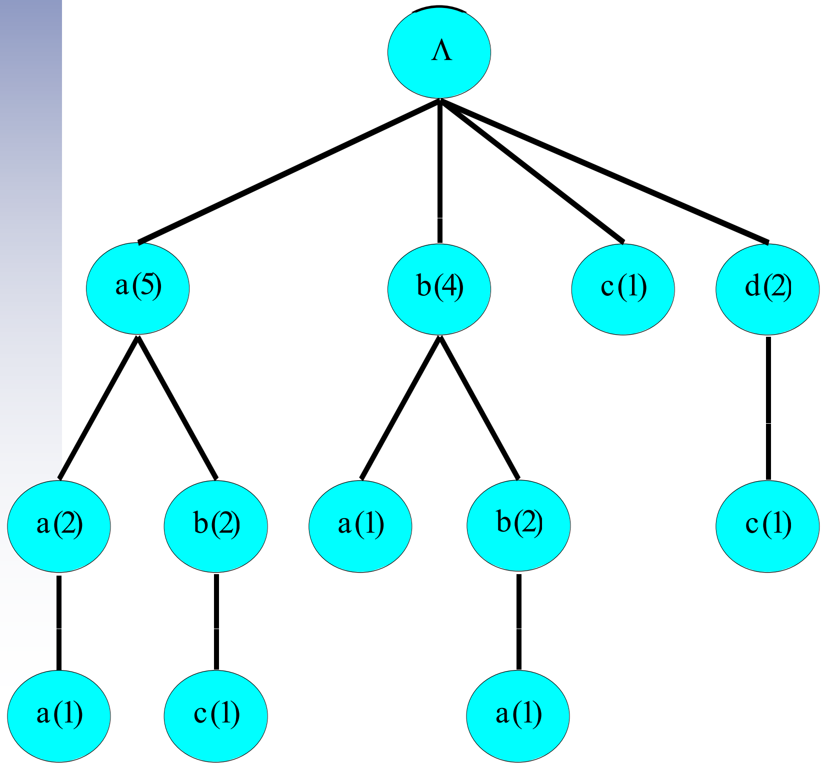
```
initialize dictionary := empty
initialize phrase w := null
loop
    wait for next symbol v
    if (w.v in dictionary)
      w := w.v
    else
      encode <index(w),v>
      add w.v to dictionary
      w := null
    endif
forever
```

Procedure Decoder

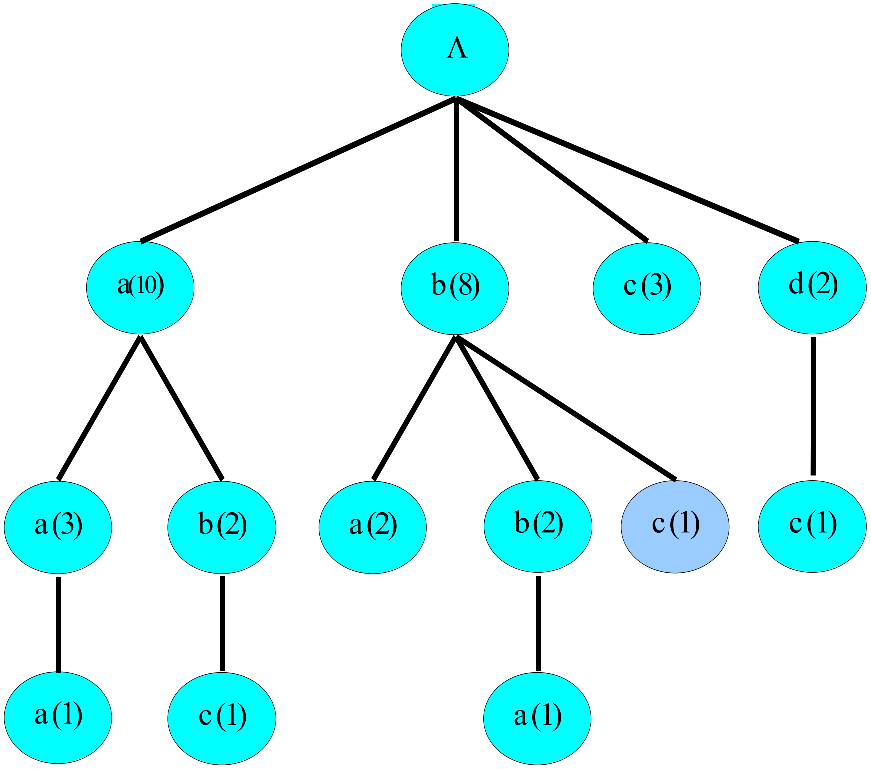
```
initialize dictionary := empty
loop
    wait for next codeword <i,s>
    decode
      phrase := entry[i].s
    add phrase to dictionary
    increment frequency
        for every prefix
        of every suffix
        of phrase
forever
```

Classical/Enhanced Dictionary

a, a a, b, a b, b b, b b a, a b c, c, d, d c, b a, a a a, …



Classical version



Enhanced version

User Mobility Model

- Movement history
  - A string "$v_1 v_2 v_3 \ldots$" of symbols from alphabet ϑ
- User mobility model: $\mathcal{V} = \{V_i\}$
  - A stationary stochastic process where V_i assumes values $v_i \in \vartheta$
- Stationarity:
  - $\mathcal{V}=\{V_i\}$ is stationary if

    $$\Pr[V_1 = v_1, V_2 = v_2, \ldots, V_n = v_n]$$
    $$= \Pr[V_{1+l} = v_1, V_{2+l} = v_2, \ldots, V_{n+l} = v_n]$$
- Ergodicity: Ensures order-*k* Markov approximation
- Physical meaning
  - Choice of routes dictated by habitual pattern of life
  - Patterns may be piecewise
  - Route length user dependent

Characterization of Uncertainty

- Entropy: $H(X) = -\sum_{i=1}^{|X|} p_i * \log(p_i)$
- Joint entropy: $H(X,Y) = -\sum_{x \in \mathcal{X}} \sum_{y \in \mathcal{Y}} p(x,y) \lg p(x,y)$
- Entropy rate
  - Per symbol entropy (when the limit exists)

$$H(\mathcal{V}) = \lim_{n \to \infty} \frac{1}{n} H(V_1, V_2, \ldots, V_n)$$

  - Conditional entropy given the past (when the limit exists)

$$H'(\mathcal{V}) = \lim_{n \to \infty} H(V_n \mid V_{n-1} V_{n-2} \cdots V_1)$$

- Universal model - for a stationary process {Vi }
  - H' (V_n | V_{n-1}, V_{n-2}, …, V_1) decreases with increasing n
  - Limiting case: H' ($\mathcal{V}$) = H($\mathcal{V}$)

Complexity Aspects of LZ78

- Optimal and adaptive to entropy rate

$$\lim_{n\to\infty}\sup \frac{1}{n}\left[len\left(V_1, V_2, \ldots, V_n\right)\right] = H\left(\mathcal{V}\right)$$

with probability 1.

- Number of updates same as the number of parsed phrases

$$c\left(n\right) = O\left(n / \left(\log n - \log\log n\right)\right)$$

- Number of phrases in dictionary = *c* (*n*)
- Number of nodes in the trie = *c* (*n*)
- Effective number of states *c* (*n*)
- Effective Markov order

$$k = O\left(\log c\left(n\right)\right) = O\left(\log n - \log\log n\right)$$

The Rank Paging Technique

- Symbol ranking problem in text compression
  - Predict next symbol by decreasing probabilities
  - Estimate probabilities blending contexts of different orders
  - Exclusion principle (using escape probabilities)

- Symbol ranking problem for terminal paging
  - Current context available from last update
  - Predict incumbent paths by blending high to low orders using vine pointers and escape probabilities
  - Given future paths, assign probabilities to cells
  - Un-condition to estimate cell residence probabilities

Symbol Ranking:
Predict Current Cell

Phrase	Pr [Phrase]	a	b	c	d
a	1/3 + 2/3 {1/5 + 1/2 (5/23)} = 0.5391	0.5391	0	0	0
aa	2/3 {1/10 + 1/2 (2/23)} = 0.0957	0.0957	0	0	0
aaa	2/3 {1/2 (1/23)} = 0.0145	0.0145	0	0	0
ab	2/3 {1/2 (1/23)} = 0.0145	0.0073	0.0073	0	0
abc	2/3 {1/2 (1/23)} = 0.0145	0.0048	0.0048	0.0048	0
b	2/3 {1/10 + 1/2 (3/23)} = 0.1104	0	0.1104	0	0
ba	2/3 {1/2 (2/23)} = 0.0290	0.0145	0.0145	0	0
bb	2/3 {1/2 (1/23)} = 0.0145	0	0.0145	0	0
bba	2/3 {1/2 (1/23)} = 0.0145	0.0048	0.0097	0	0
bc	2/3 {1/10 + 1/2 (1/23)} = 0.0812	0	0.0406	0.0406	0
c	2/3 {1/2 (3/23)} = 0.0435	0	0	0.0435	0
d	2/3 {1/2 (1/23)} = 0.0145	0	0	0	0.0145
dc	2/3 {1/2 (1/23)} = 0.0145	0	0	0.0073	0.0073
Sum		0.6807	0.2018	0.0962	0.0218

Dictionary Implementation

- Ziv-Lempel trie stored in a hash table
  - Static memory management: Experiment with size ($M = 2^p$)
  - Open addressing with double hashing

$$h(k,i) = (h_1(k) + i\, h_2(k)) \bmod M$$

$$h_1(k) = \lfloor M\, ((k\, A / 2^w) \bmod 1)\rfloor$$

$$h_2(k) = 2\, [\, k \bmod ((M/2) + 1)] + 1$$

where $h_2(k)$ is always odd, and hence relatively prime to M

  - Flush when fills up: Experiment with threshold

- Hash table entries are trie nodes
  - Flag used to mark a valid entry as opposed to empty bin
  - *i*-th child of a node found by hashing both node id and i

Implementation of Encoder/Decoder

- Encoder
  - Interacts with the update framework
  - Encapsulates a lightweight Dictionary
  - Holds trie nodes only for matching

- Decoder
  - Interacts with both update and paging framework
  - Encapsulates a heavyweight Dictionary
  - Holds trie nodes for matching and prediction
  - Trie nodes contain the frequency counts
  - Suffix matching possible by implicit vine pointers

Synthetic Trace for Simulation

- Cellular Network Topology
  - Average connectivity of six neighboring cells
- Activity-based Mobility Model
  - Parameters that simulate a real-life user
  - Time distribution of lengths of stay in each cell
  - Different schedule during weekend
- Activity based call Model
  - Call arrival times are exponentially distributed
  - Call durations are normally distributed with given mean and standard deviation reflecting charges
  - Integrated with hand-off, call waiting, etc.

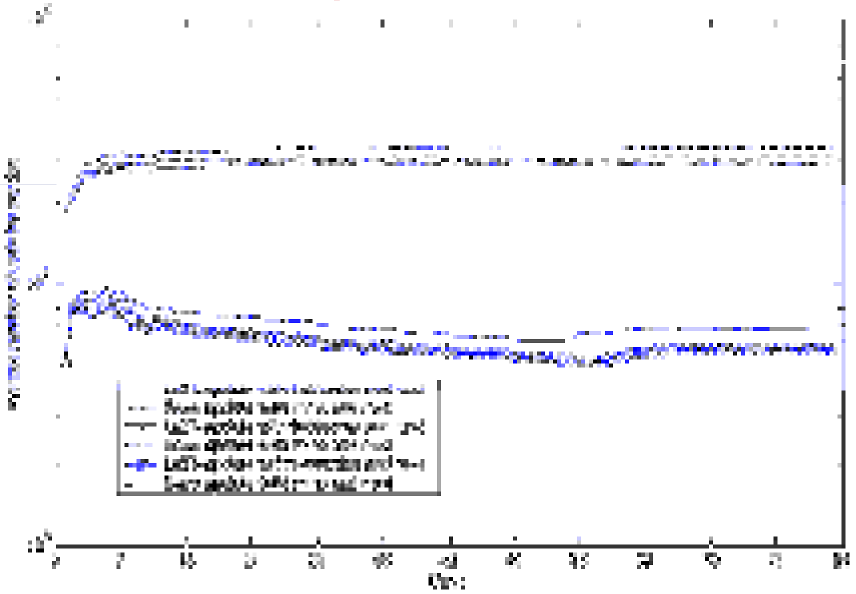
Simulation Results

- Best schemes for basic updates (capture)
  - Location Area size (9 – 16 cells)
  - Time threshold (30 / 60 minutes)
  - Movement threshold (3 – 4 cell crossings)
  - Distance threshold (1 – 3 cell diameter)
  - Performance variation: Not a whole lot!

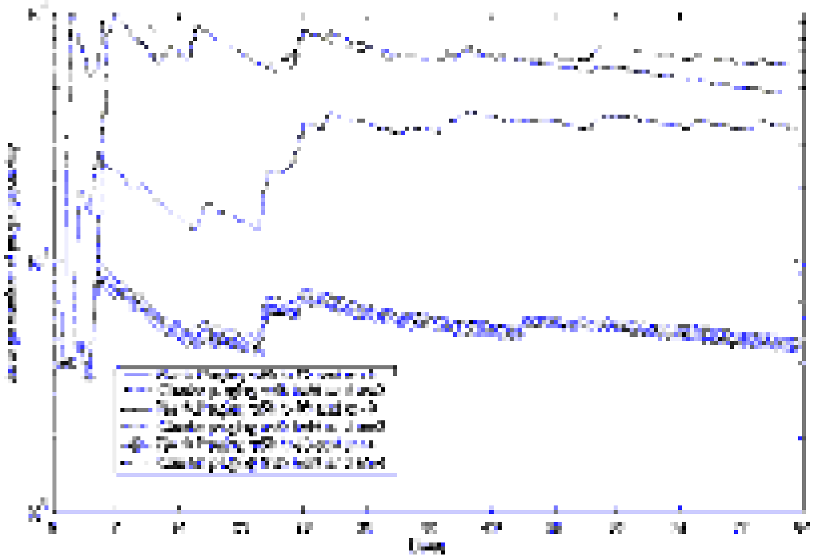
- When LeZi-update is invoked
  - Visible learning characteristic
  - 2 – 5 times improvement in update cost
  - 5 – 8 times improvement in paging cost

Performance Improvements

Update Cost



Paging Cost



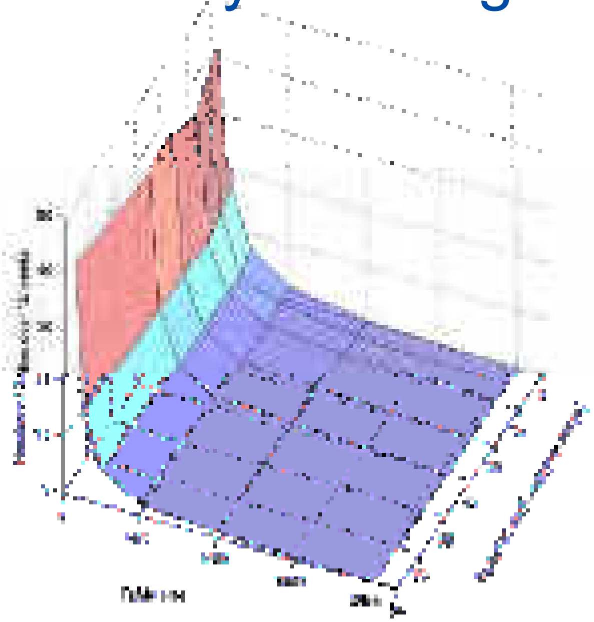
Sajal K. Das

Importance of Stationarity

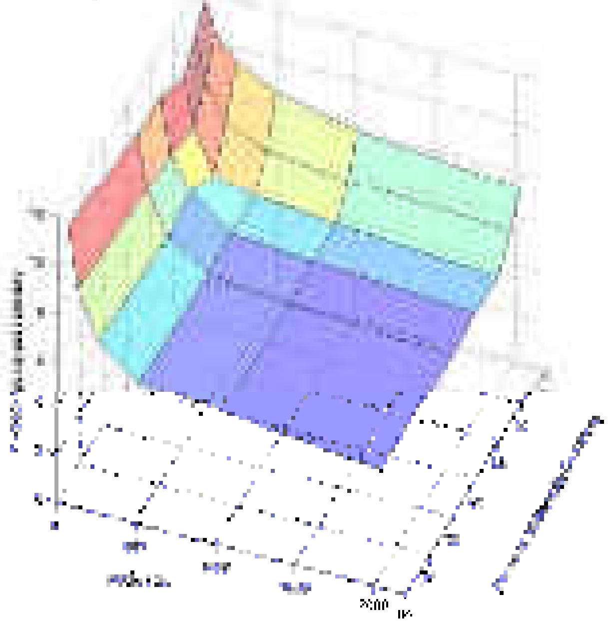
- Stationary movement pattern
  - Asymptotic convergence guaranteed
  - Stationary pattern changes sooner or later
- Piecewise stationary movement pattern
  - A sensible choice in practice
  - LeZi-Update learns each stationary pattern
  - Pattern must change comparatively slower
- Size of hash table
  - Lower table size hurts update cost
  - Higher table size hurts paging in low stationarity
  - Number of flushes is a good measure of learning

Impact of Stationarity

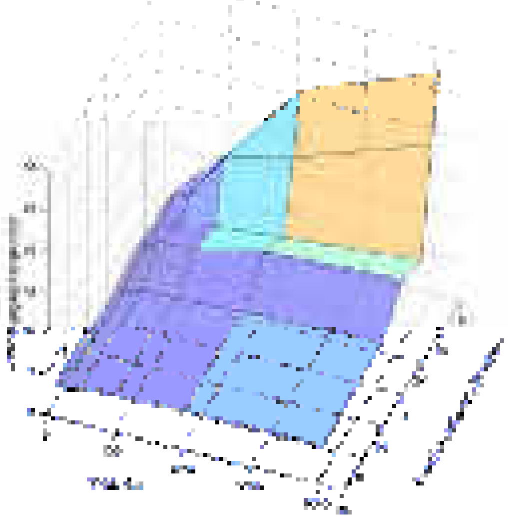
Dictionary Flushing



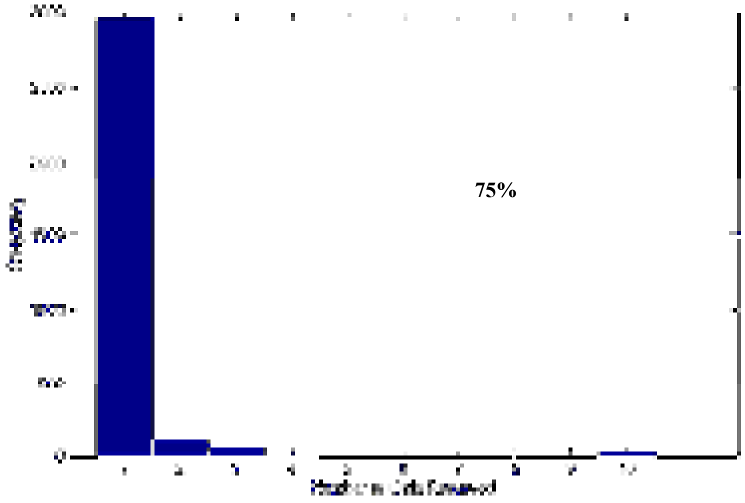
Update Cost

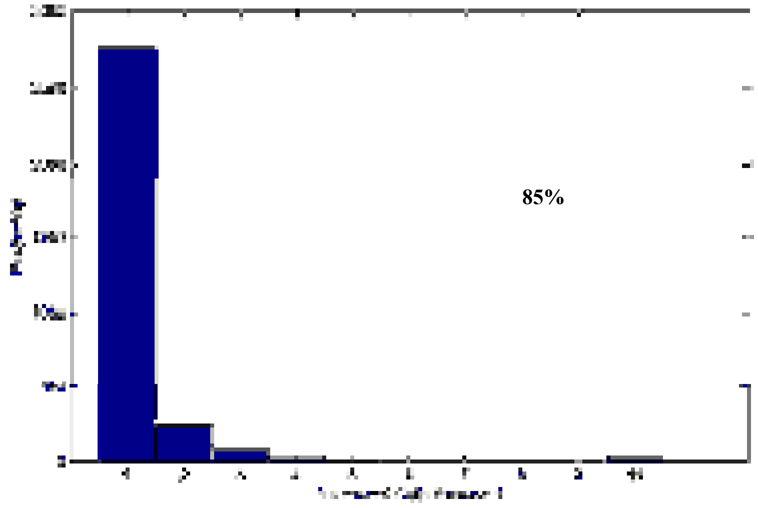


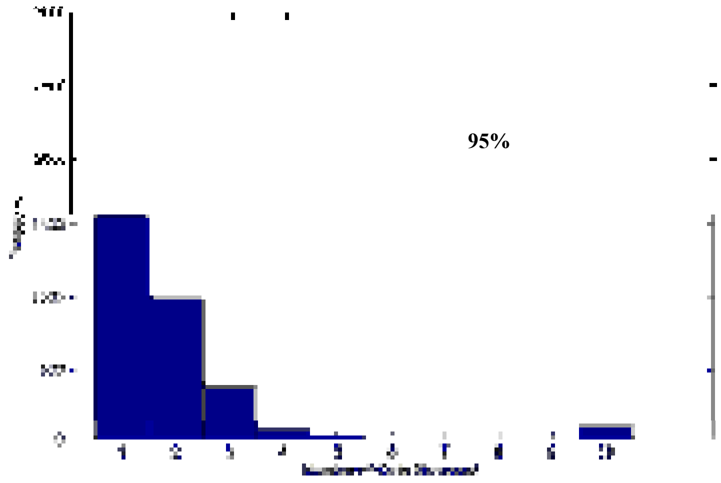
Paging Cost

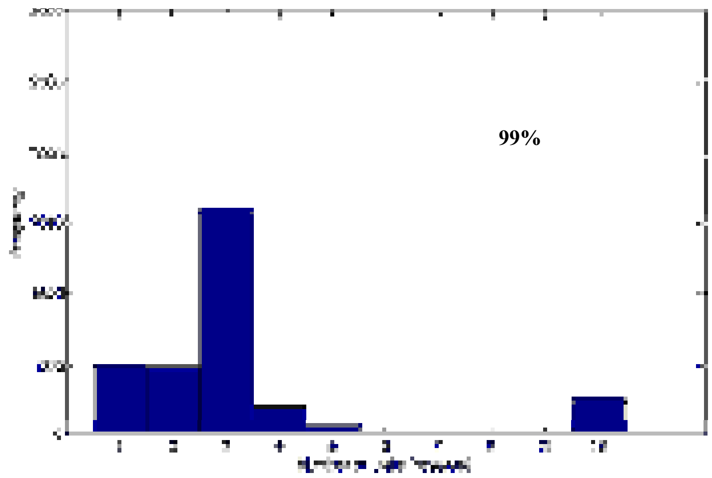


Early Channel Reservation Needs









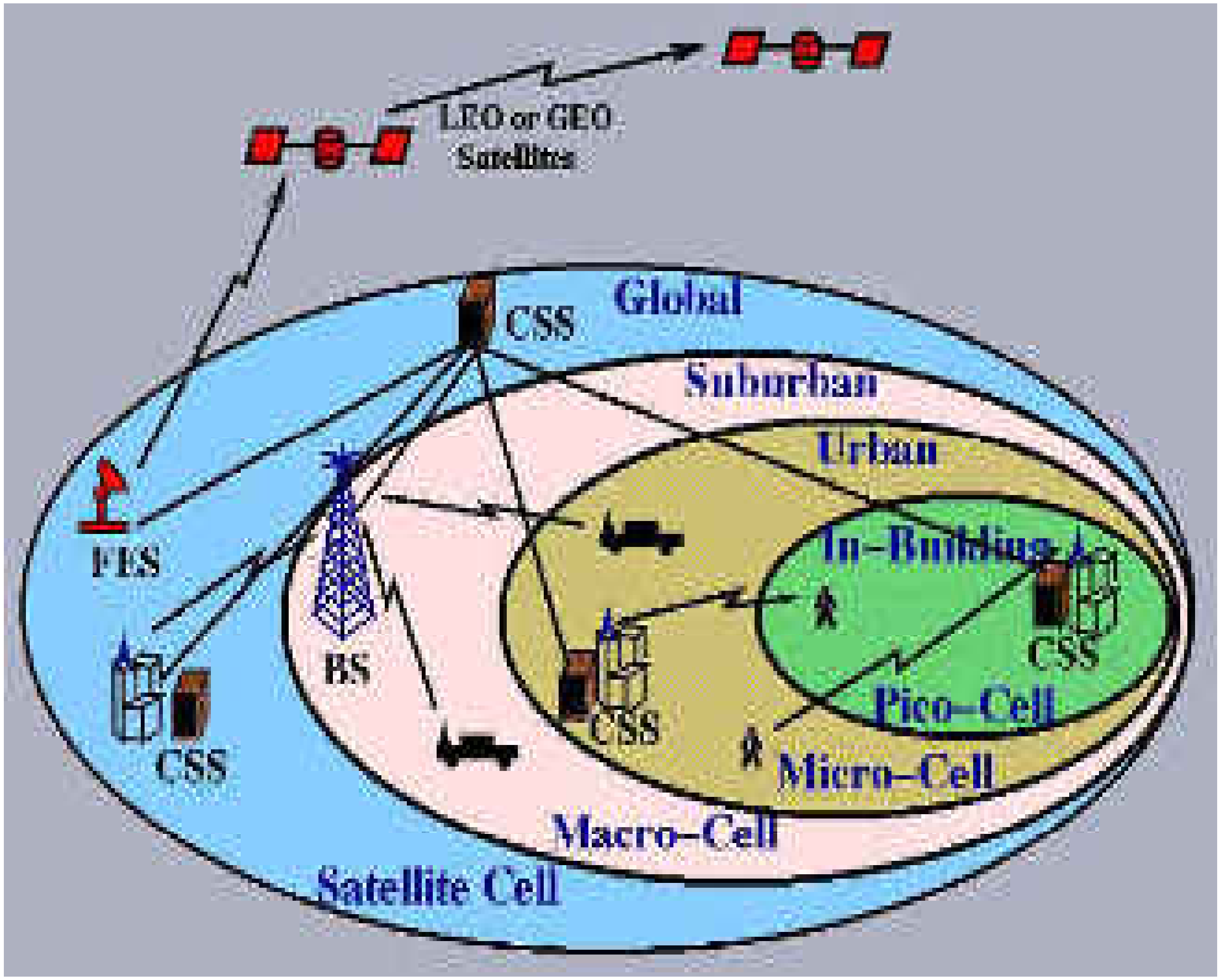
Conclusions

- Location prediction: A key solution to many problems
- Works only when there are identifiable patterns in user behavior (stationarity)
- A good compressor is a good predictor
- LeZi-update used LZ78 compressor
- LZ78 is a universal compressor: It adapts!
- Trace driven simulation is best – synthetic trace using activity-based model is second alternative

2.5G Components

- SGSN (Serving GPRS Support Node)
  - Mobility management (at routing area level; terminal mobility)
  - Routing
  - Data compression
  - Authentication
  - Billing (based on the usage of own network and air interface)
- GGSN (Gateway GPRS Support Node)
  - Provides interworking functionality to other PLMNs and external data networks (such as the Internet)
  - IP Address Allocation
  - Host Configuration Functions
  - Tunnels packets on behalf of the mobile (i.e., performs common IP router functions)
  - Maintains location information of data users
  - Billing (based on the usage of the external network resources)

3G/4G Architecture



- ❑ Hierarchical cell structure
- ❑ Vertical handoff
- ❑ Global roaming

Global Roaming

- Intra-system Roaming
  - Movement between different tiers (macro-, micro- and pico-cells) of the same system
- Inter-system Roaming
  - Movement between different backbones, protocols, or service providers — terrestrial/satellite, IS-95/GSM, etc.
  - Vertical handoff
- Challenges and Open Problems
  - Inter-system Hand-off and Location Management
  - Addressing, Identification & Security
  - Database Management
  - Routing & IP Mobility

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Lecture 5: Wireless Internet

- Internet Mobility
  - Micro-Mobility Protocols
  - Macro-Mobility Protocols
- Mobile IP
- TeleMIP / IDMP

What is Wireless Internet?

Combine mobility with the rich multimedia content of the Internet

Wireless Internet = Wireless + Internet + Internet Mobility

Wireless

- Ubiquitous services
- Mobility key driver
- Voice becoming commodity
- Advanced services
- 38%: “most desired service” is Internet
- ~300 million subscribers

Internet

- 20+ million hosts
- ~175 million users
- Users doubling every 6 months
- 1000% annual traffic growth
- Base on global “networked economy”

- 75% laptop users are also wireless voice users
- 95% of palm size devices are also Internet users
- Ideal candidates for wireless data

Wireless Internet

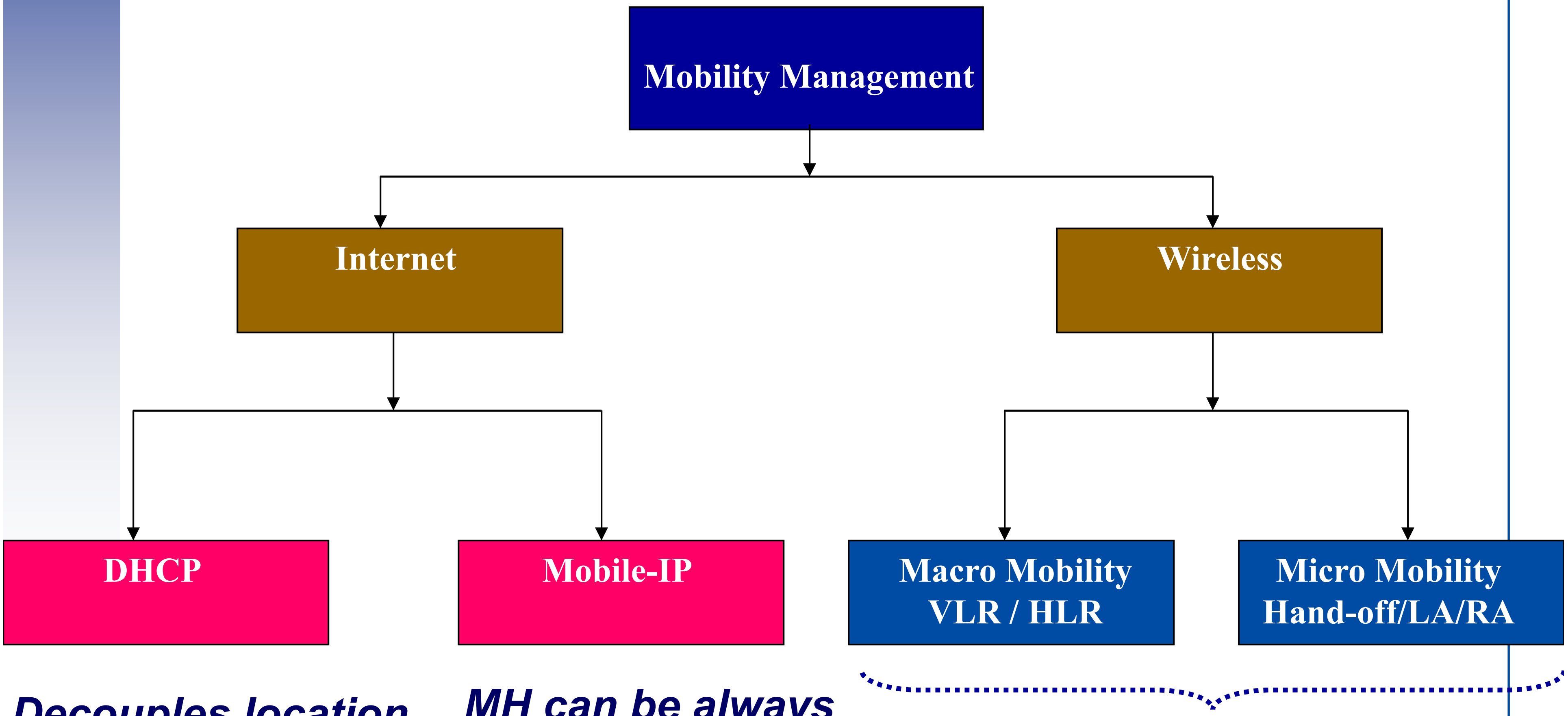
Motivation

- Wireless and Internet are coming together creating synergy, significant opportunities and challenges
- Wireless mobile multimedia services will be a major drive for wireless Internet
- Technology challenges for wireless multimedia will be centered around how to support “simple, secure, reliable transactions for mobile users”

Benefits

- Cost Savings
  - Lowers networking infrastructure costs dramatically
  - Leverage Moore’s Law
- New Sources for Revenue (for wireless operators)
  - Drives additional revenue growth via value-added services & applications
  - Reduces churn rate by satisfying broader set of customer needs
- IP Evolution
  - Use IP-based building blocks and create data network overlays
  - Offer IP services with high data rates
- Future Proof
  - IP is the protocol of choice for new services and applications
  - Technology cost curve favors IP
  - Leverages the IP innovation cycle happening in the wire-line world

IP Mobility Management



Mobility Management

- **Internet**
  - **DHCP**
  - **Mobile-IP**
- **Wireless**
  - **Macro Mobility**
VLR / HLR
  - **Micro Mobility**
Hand-off/LA/RA

Decouples location significance from routing

MH can be always reached with a given IP address

Internet Mobility

Static mobility: User terminal able to move from one network (sub-network) to another network to receive service

Dynamic mobility: User moves from one network (sub-network) to another during service session time without interruption. The challenge is to maintain session quality and integrity.

IFTF defined dynamic protocols at Network layer

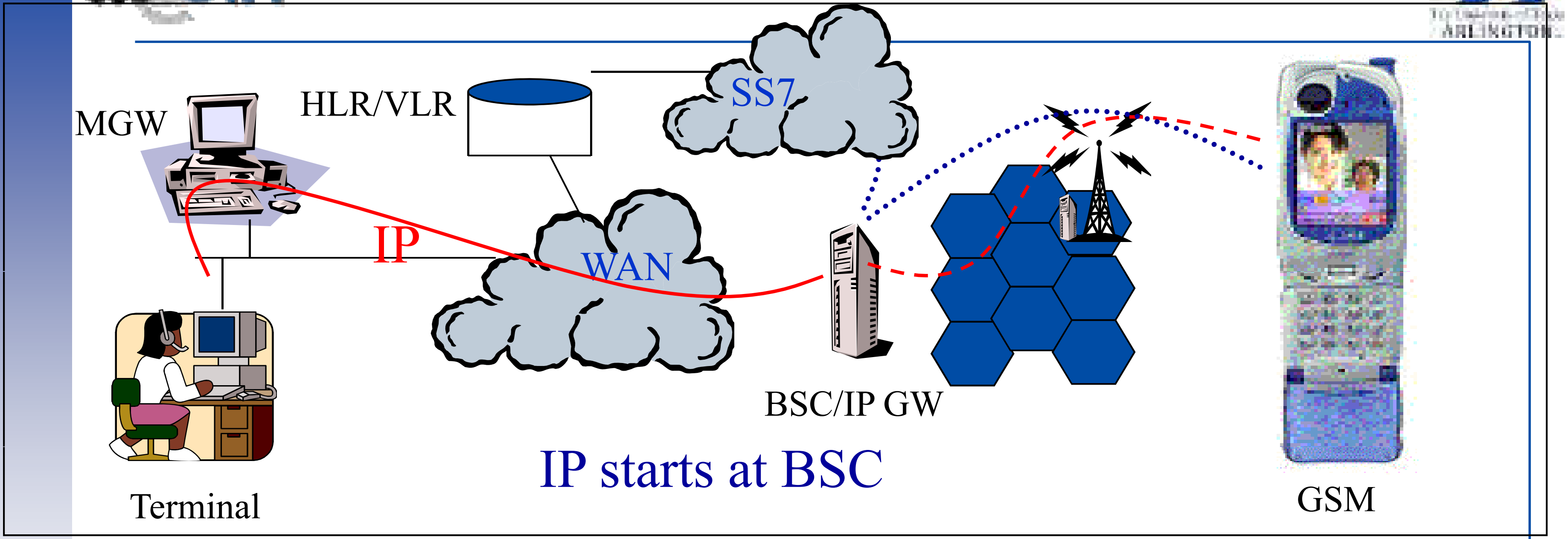
DHCP (Dynamic Host Configuration Protocol)

Mobile IP

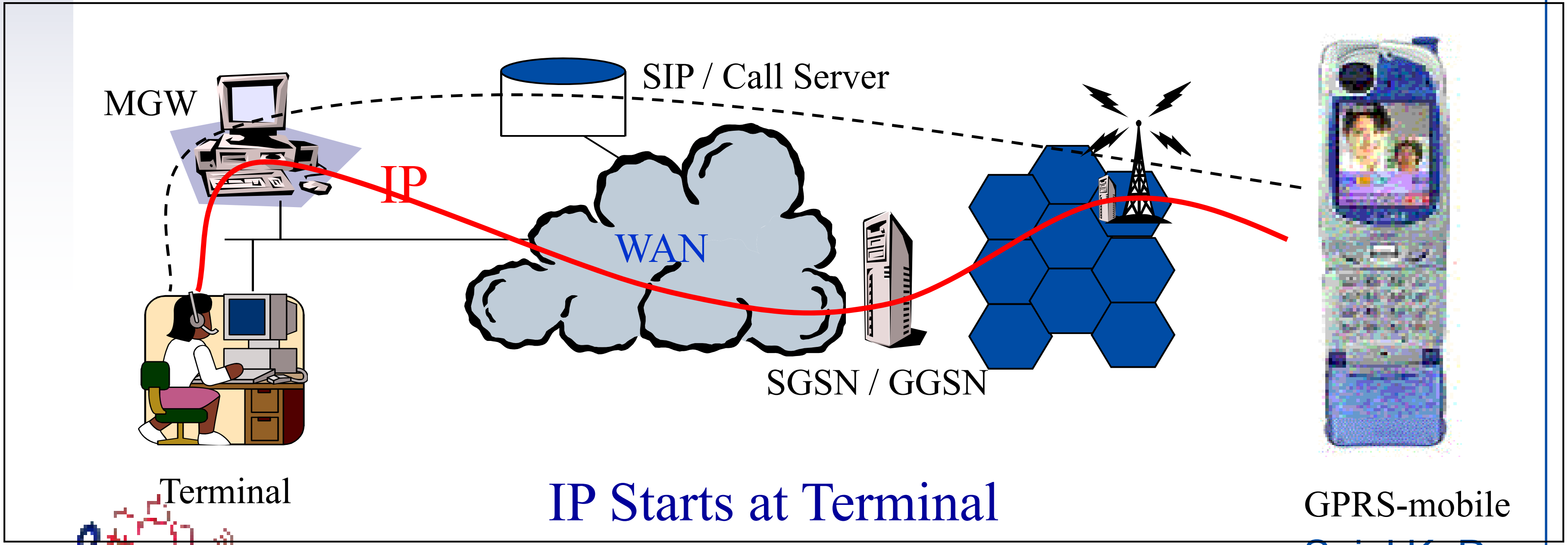
Macro Mobility: Mobility between networks (sub-networks)

Micro Mobility: Mobility between antennas of base stations or Access Points of the same network (sub network).

Wireless VoIP



IP starts at BSC



IP Starts at Terminal

Mobile IP

Two new Entities: Home Agent (HA), Foreign Agent (FA)
CH (Corresponding Host) can reach HA using IP address

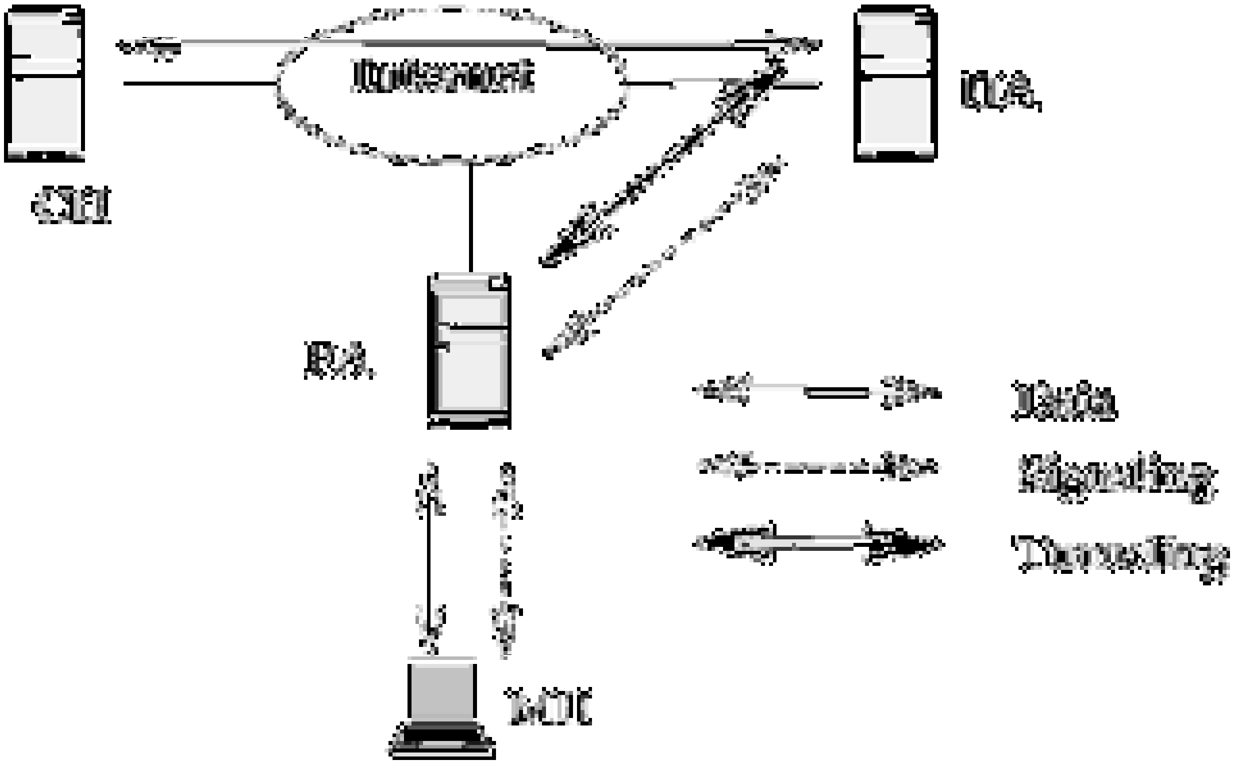


Figure 2: Packet routing in Mobile IP

Steps of Mobile IP

1. ***Mobile Agent Discovery***: Mobile Agent sends advertisement messages. Listening to this message, MH knows whether it is a HA or FA
2. ***Registration with Home Agent***
3. ***MH Obtains COA (Care of Address):*** If the MH is in the domain of FA, it gets COA by:
    Listening to the advertisement of FA
    DHCP
    PPP
4. MH then registers COA with its HA
5. HA ***redirects packets for MH to COA using encapsulation by tunneling***
6. Packets are ***de-capsulated at FA or MH***

Mobility Management

Home System	***Cellular***	***Mobile IP***
– In-session Mobility :	Hand-off	?
– Location Management	Registration	Registration
– Terminating routing:	Paging	COA
Foreign System		
– In-session Mobility	Hand-off	?
– Location Management	Registration	Registration
– Terminating Routing	Paging	COA
Inter Domain (Global Mobility)		
Mobility of security key	RAND/SERS	AAA

Limitations of Mobile IP

- ***Very High update latency***: Large Hand-off delay
- ***Large signaling load*** in the network
- ***Triangular routing*** of packets:

  - ***transmit binding message directly to CN***
    Increases location update latency.
  - ***IPv6 mobility management*** as integral part of IP protocol. Location update binding message is directly transmitted to list of CN's maintained at the mobile. Increase location update latency
- ***Long outage duration***
- Does not support paging: ***Power management***
- ***Support of QoS is complex during mobility***. New RSVP reservation required for every COA (HAWAII avoids this by using single COA in a domain).
- ***Complex Security verification on Foreign domain***

Mobility Challenges

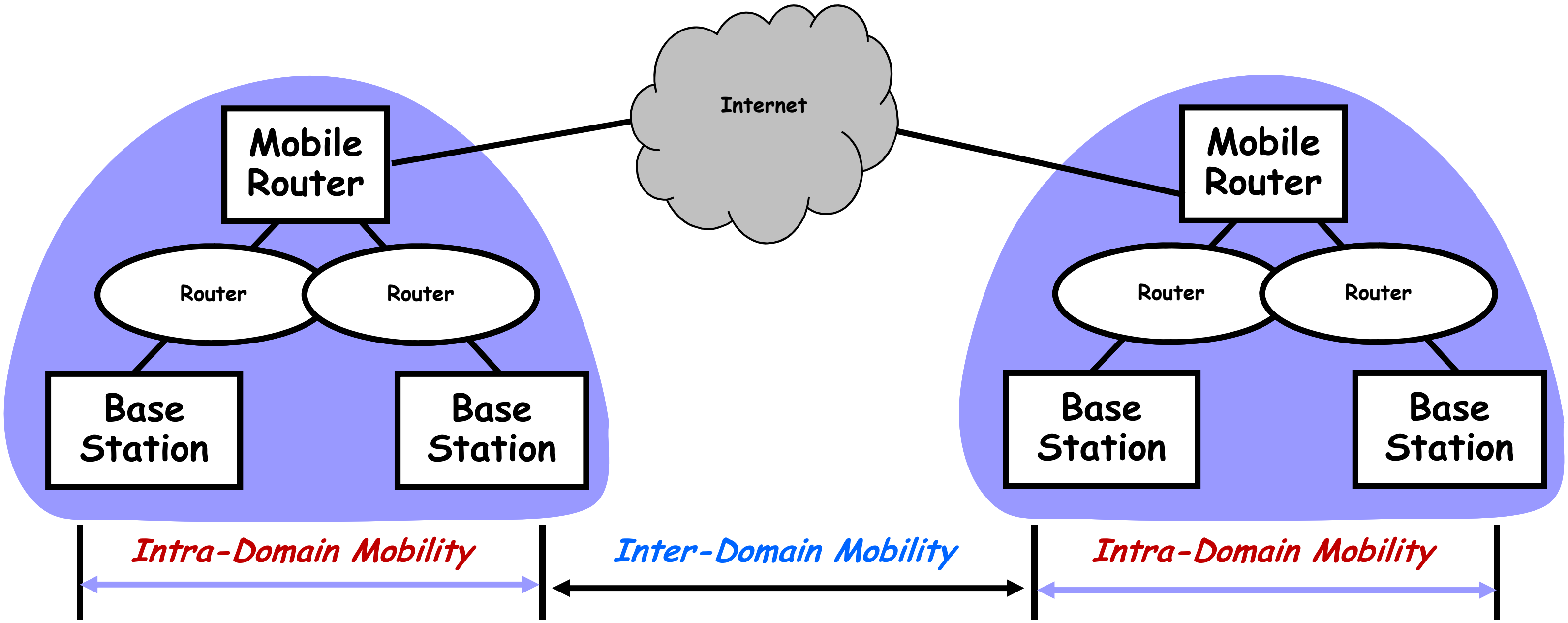
- Inter-operability between heterogeneous networks
  - Indoor systems (IEEE 802.11, Bluetooth, Active badges)
  - Campus-wide (Point-to-point connected 802.11 LANs)
  - Metropolitan area (Metricom Ricochet)
  - Land-mobile systems (Cellular/PCS)
  - Satellite based systems (Satellite phones, GPS)

- Service expansion
  - Real-time multimedia (audio/video/text) with QoS support
  - Data services (Internet applications included)
  - Billing/accounting, name/address resolution
  - Security/authentication
  - Location-aware (Context-aware) services

- Location tracking
  - Multi standard devices and appliances
  - Routing, IP mobility, inter-system hand-off / location mgmt
  - Context of space and time (wide range of granularity)

What is Internet Mobility?

- A mobile node can be reached by a unique IP address when roaming in the Internet
  - Intra-domain (Micro) mobility
    - Movement of Mobile Node (MN) across subnets within a single domain.
  - Inter-domain (Macro) mobility
    - Movement of MN across administrative domains or geographical regions



Internet Mobility Mgmt Schemes

- Inter-domain (Macro) Mobility: Mobile IP
- Intra-domain (Micro Mobility):
  - IDMP (UT Arlington, IBM Watson, Telcordia Technologies)
  - Cellular IP (Ericsson, Columbia University)
  - HAWAII (Lucent Technologies)
  - Mobile IP Regional Tunnel Management (Ericsson, Nokia) + Hierarchical Mobile IP with Fast Handoffs (Ericsson)
  - HMMP (Telcordia Technologies, Toshiba)
  - HMIPv6 (INRIA)
  - TIMIP (INESC/ISE)

Mobile IP: Inter-domain Solution

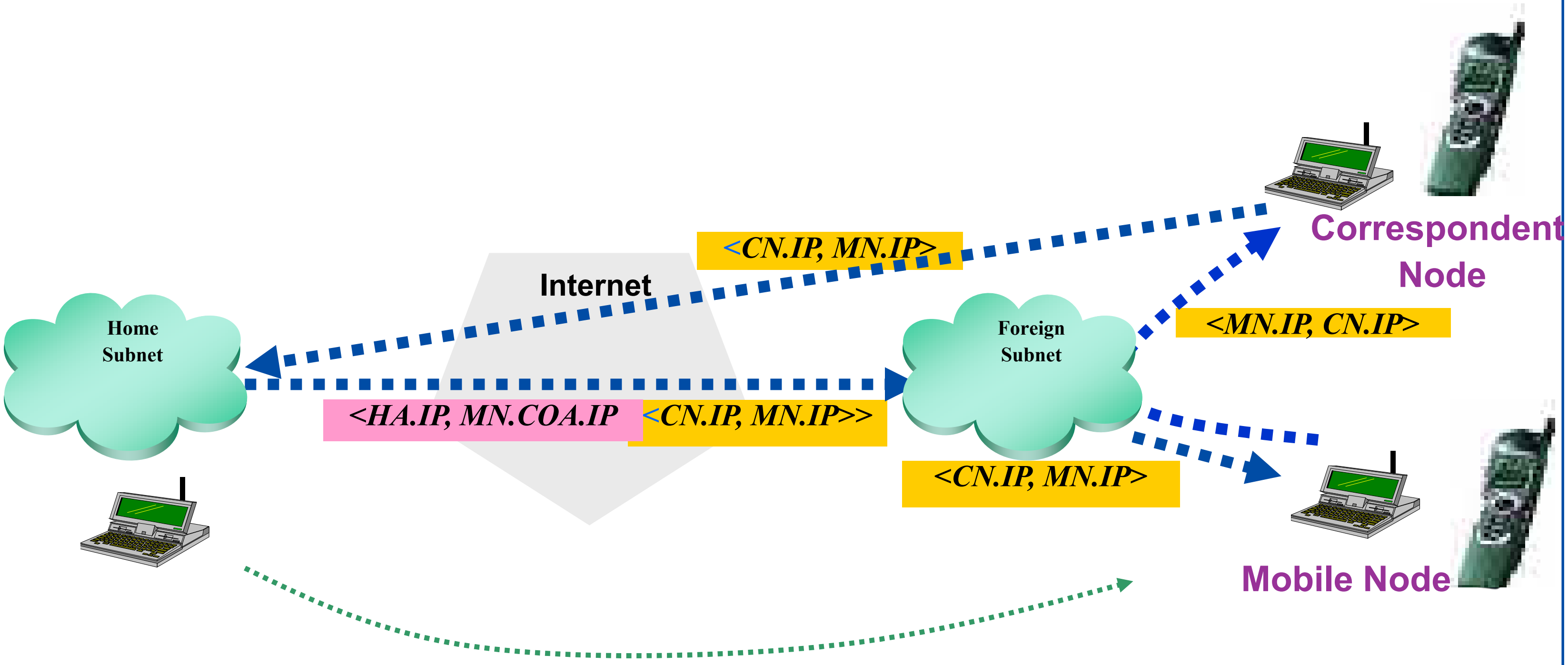
- Add mobility to conventional IP networks (IPv4, IPv6)

- Mobile IP
  - Define special entities
    - Home agent (HA)
    - Foreign agent (FA)
  - Two IP addresses
    - Identification (permanent - home network related)
    - location (variable - location dependent): *Care of Address* (CoA)
  - Authentication
    - Security Associations between User-HA, HA-FA, FA-User
    - Dynamically security association using AAA

Core operations:

- Agent discovery
- Registration
- Packets tunnelling

Datagram Delivery in Mobile IP

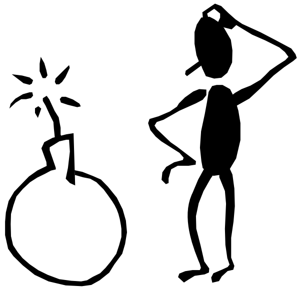


IPv4 requires packets to be intercepted by the Home Agent (HA) and tunneled to the MN's CoA.

- Route Optimized option allows Correspondent Node (CN) to tunnel directly to the MN's CoA.

IPv6 requires the MN to inform every active CN of its new CoA; every CN then re-directs packets to this new CoA.

Problems with Basic Mobile IP



- High latency of location updates
  - All location updates must travel all the way to Home Agent (HA) or Correspondent Node (CN).
- High frequency of global location update messages
  - Since address binding changes with change in every subnet, frequent generation of location updates to HA or CN.
- Inefficient use of existing public address space
  - Since HA (or CN) use the mobile's current CoA, we need at least one global address per subnet (for FA) or one global address per mobile in HA (in co-located mode).

A New Scheme: Intra-domain Mobility Management Protocol (IDMP)

University of Texas at Arlington
Sajal K. Das
Wei Wu

IBM Watson Research
Archan Misra

Telcordia Technologies
Subir Das
Ashutosh Dutta
Anthony Mcauley
Prathima Agrawal

Why a New Scheme?

Provide a scalable two-layer mobility management architecture

- Reduce the latency of location updates for intra-domain mobility.
- Reduce the frequency of global signaling messages.
- Remove the necessity for host-based routes.

Make intra-domain mobility management independent of global update mechanism

- Work with Mobile IP, Session Initiation Protocol (SIP), etc.

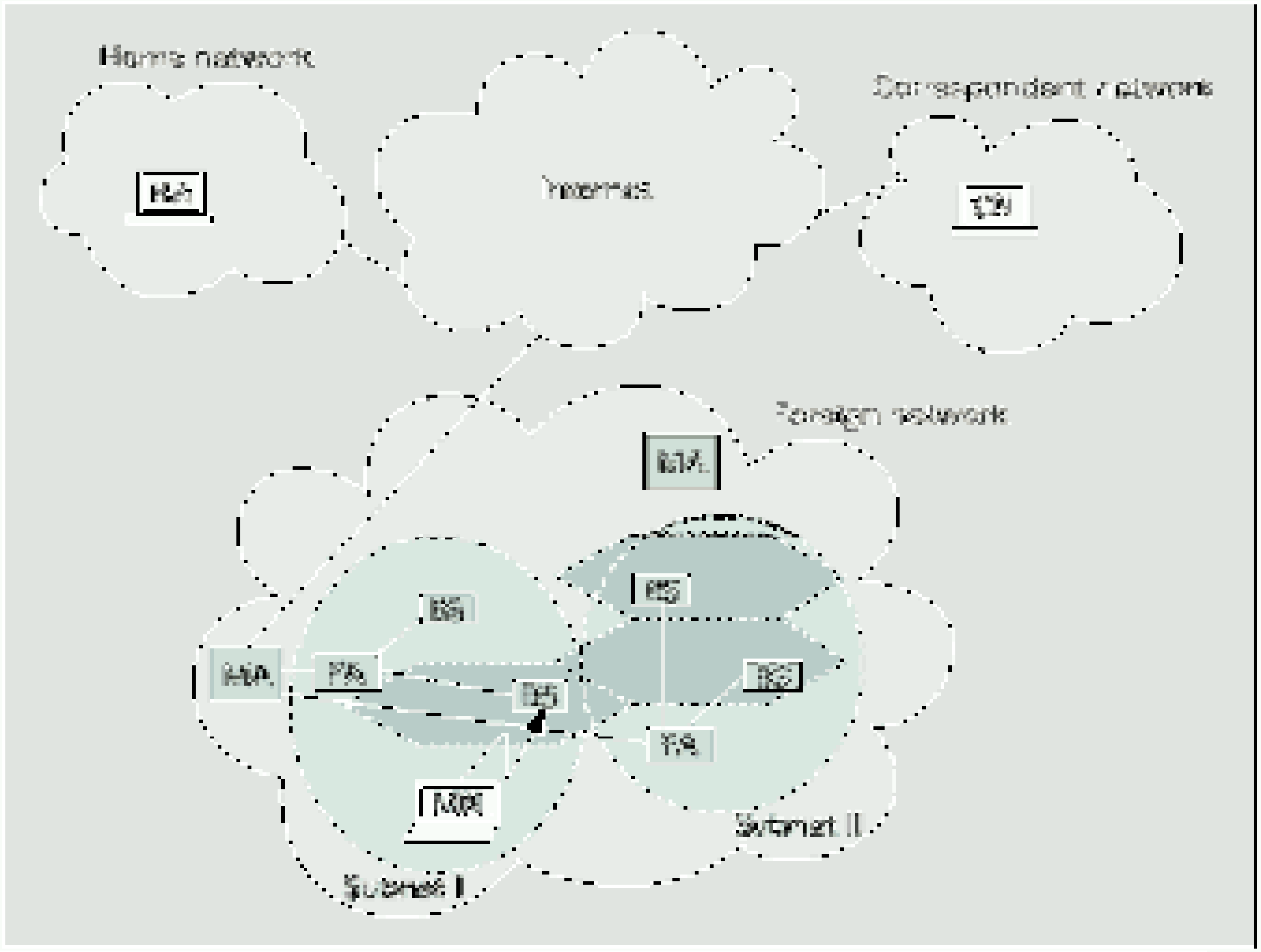
Support features of interest in intra-domain cellular mobility

- Fast and loss-less handoffs.
- Paging to reduce registration in idle state.
- Guaranteed QoS provisioning with minimal signaling.

Nomenclature Explanation

- TeleMIP (Telecommunications Enhanced Mobile IP Architecture)
  - A mobility management scheme that combines IDMP with Mobile IP (for inter-domain mobility).
- IDMP (Intra-Domain Mobility Management Protocol)
  - The protocol for managing intra-domain mobility by using Mobility Agent (MA) and Subnet Agent (SA).
- DMA (Dynamic Mobility Agent)
  - The intra-domain mobility management architecture that uses multiple MAs for load-balancing and that uses Bandwidth Broker (BB)-based QoS provisioning.

TeleMIP Architecture



TeleMIP: Telecommunications Enhanced Mobile IP

MA: Mobility Agent

BS: Base Station

MN: Mobile Node

HA: Home Agent

FA: Foreign Agent

CN: Correspondent Node

IDMP Fundamentals

Every MN is assigned two CoAs

- Global CoA (GCoA) is globally reachable and remains unchanged as long as the MN moves within a domain.
- Local CoA (LCoA) has only domain-wide scope and changes with every change in point of attachment.

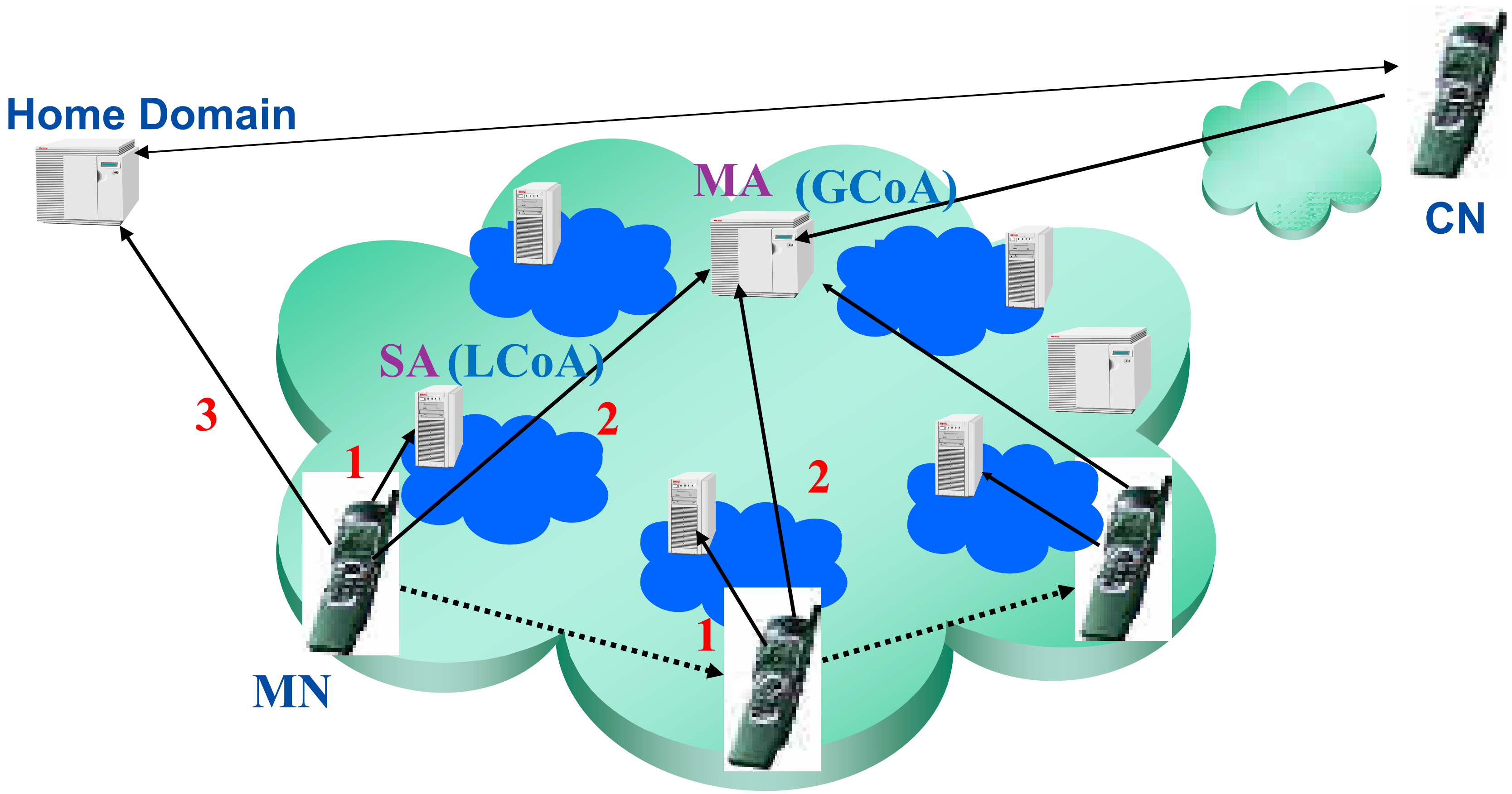
Mobility Agent (MA) acts as a domain-wide point of packet redirection

- Packets from outside (addressed to the GCoA) arrive at the MA.
- MA intercepts such packets and tunnels them to the MN's current LCoA.

During movement inside the domain, the MN only sends an intra-domain *BindingUpdate* to the MA

- No need for global signaling (to HA or other servers) unless the GCoA changes.
- Hierarchy reduces the latency of most updates, and significantly lowers the global signaling traffic load.

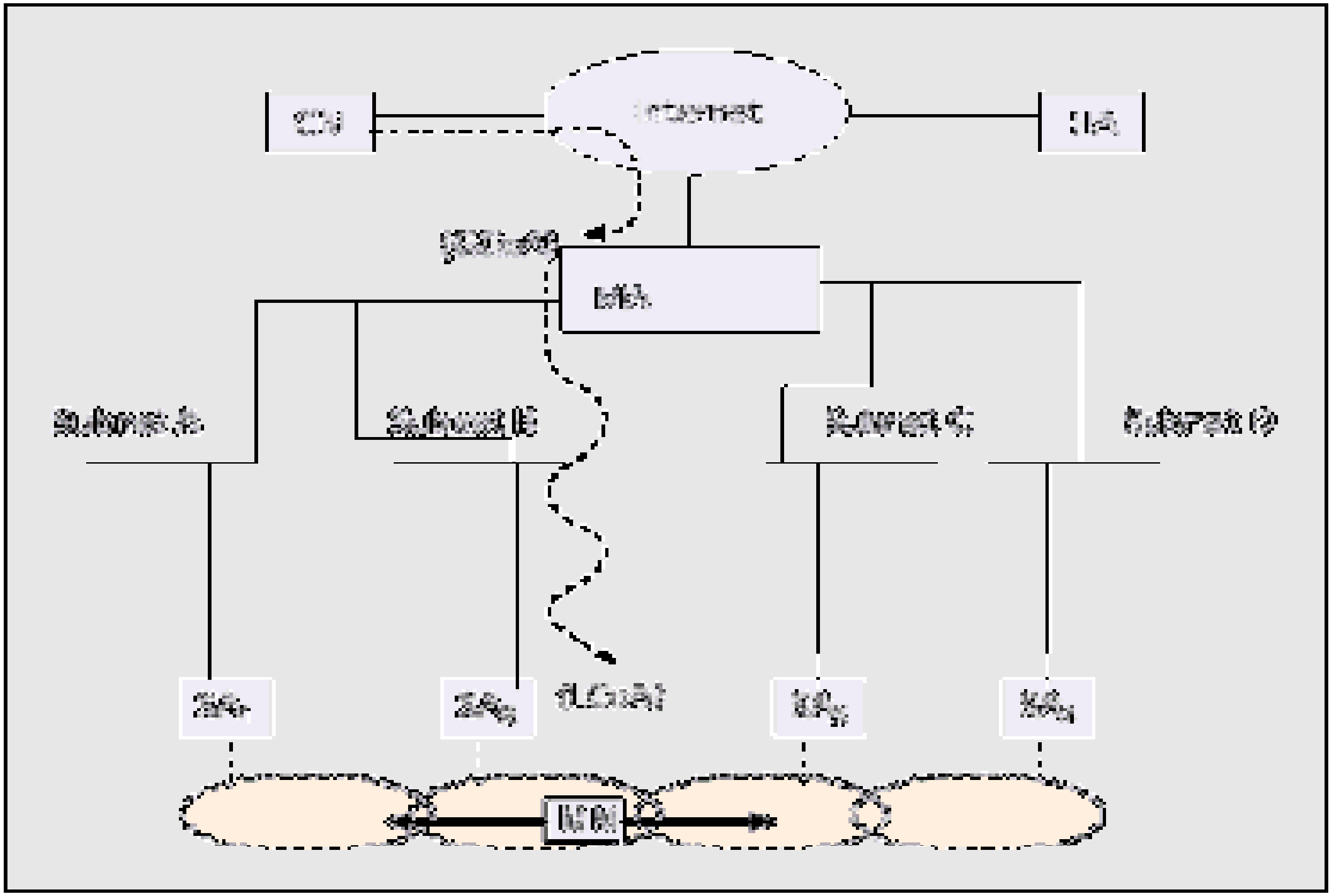
IDMP Operational Overview



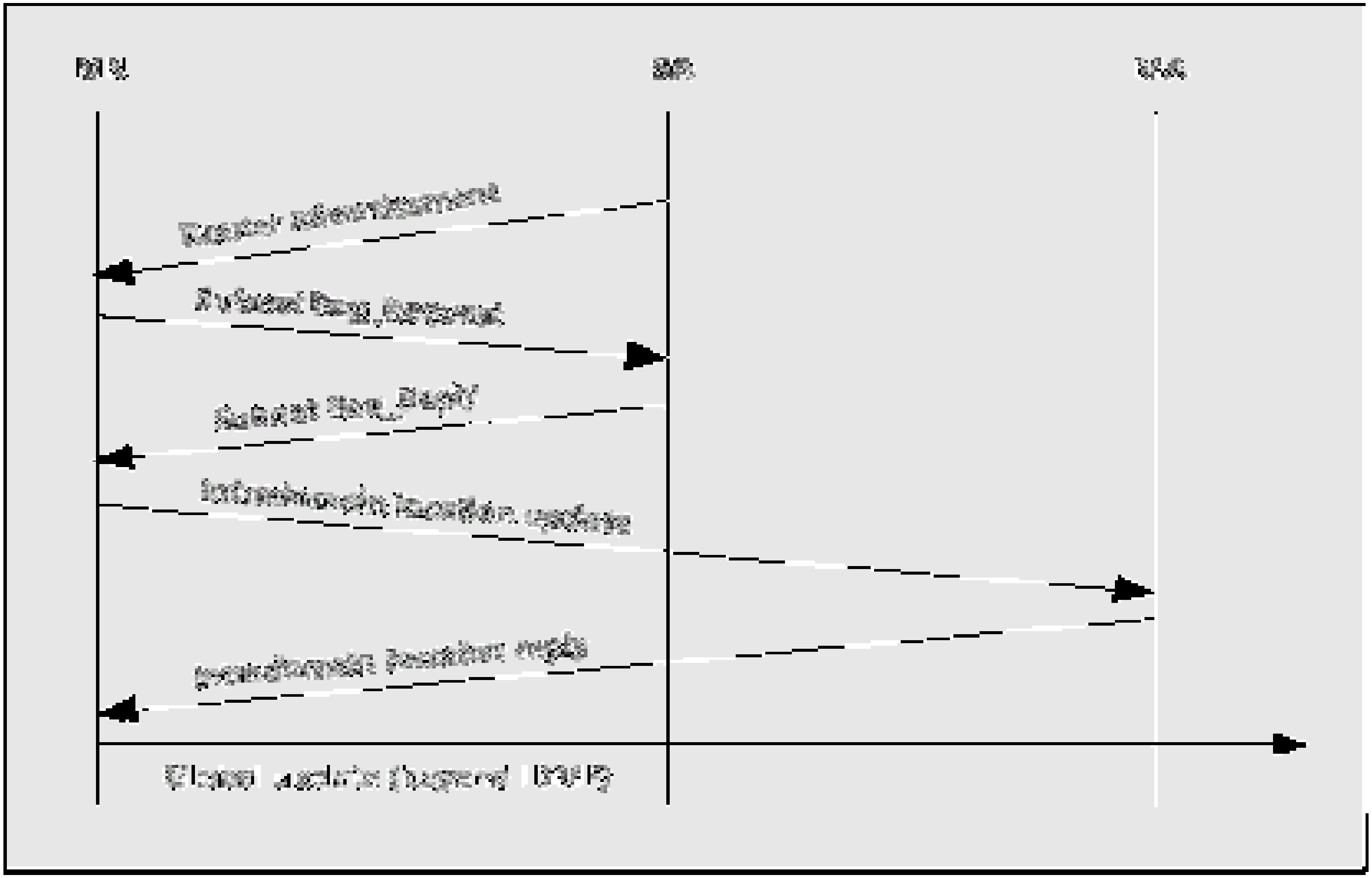
- All packets from the global Internet tunneled (re-directed) to the GCoA and are intercepted by the MA.

- MA tunnels each packet to the MN’s current LCoA.

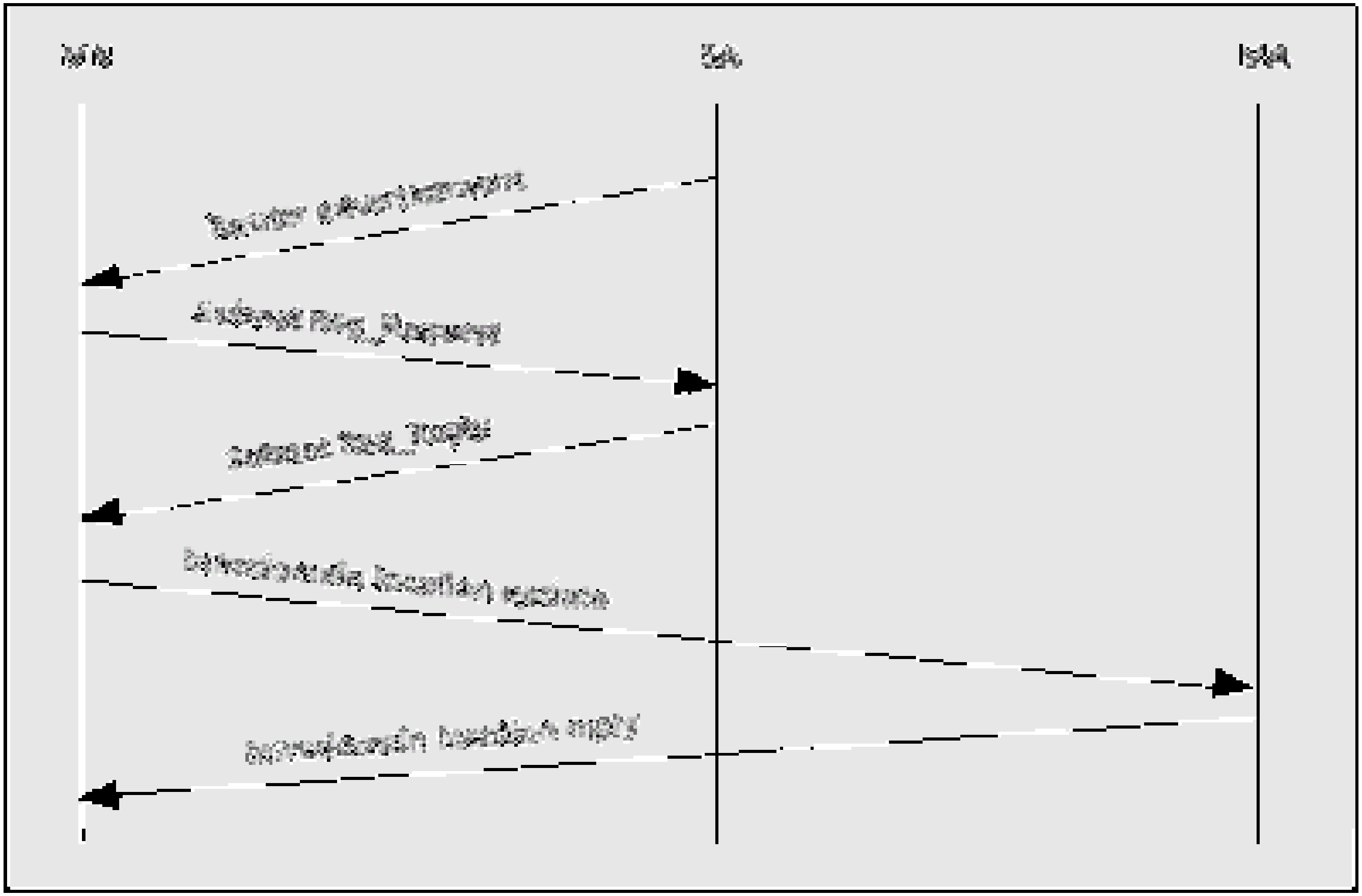
IDMP Architecture



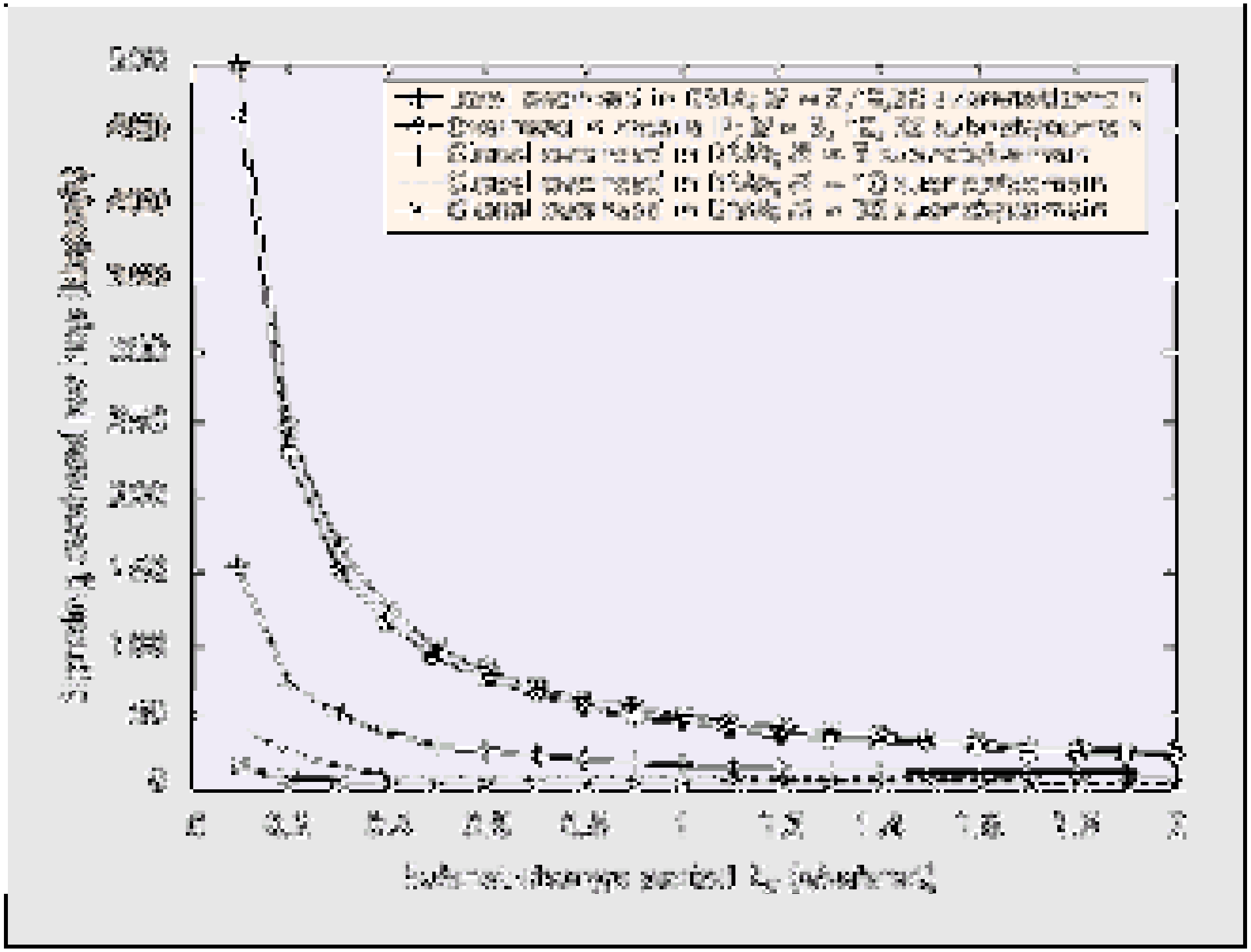
IDMP: Initial Signaling



Subsequent Intra-Domain Mobility



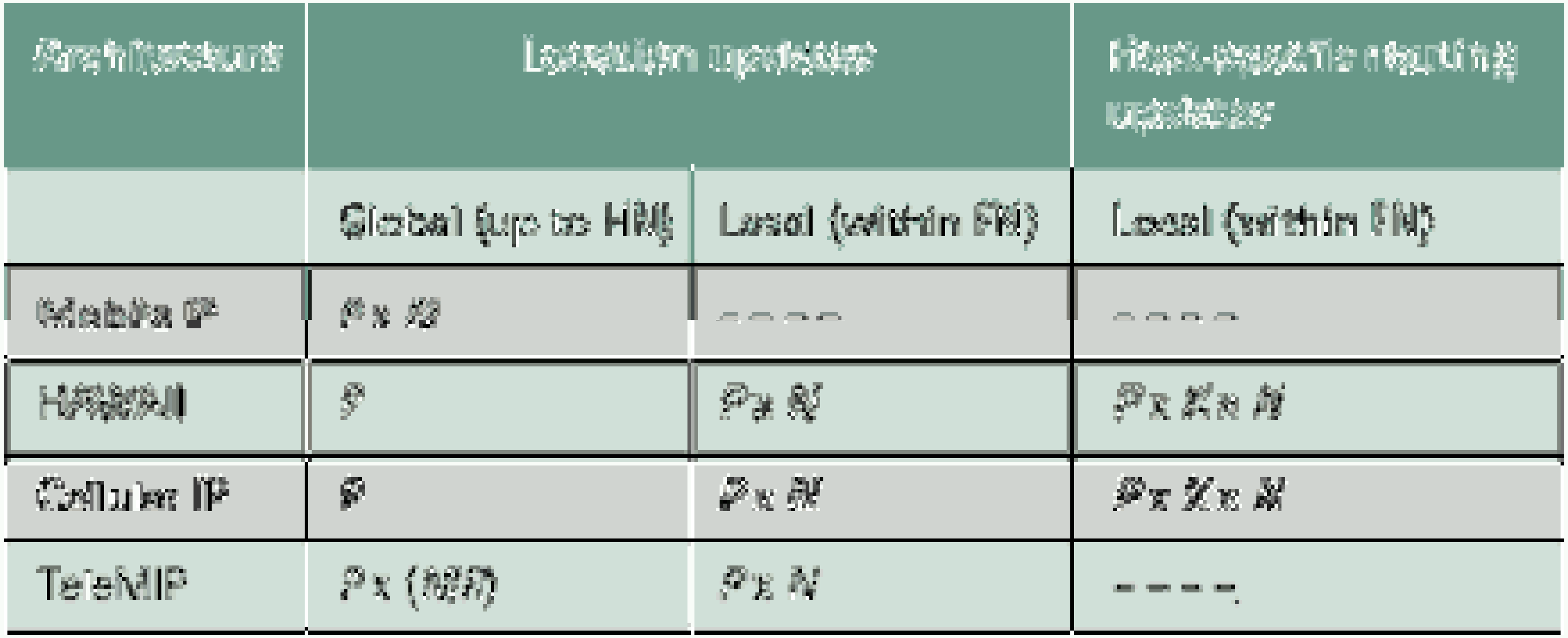
Signaling Overhead in IDMP



Input Parameters:

- Size of global registration packet: 46 Bytes
- Size of local registration packet: 50 Bytes
- Average number of hops from MN to MA: 2
- Average number of hops from MN to HA: 5

Comparison of Location Updates



Architecture	Location updates		Host-specific routing updates
	Global (up to HN)	Local (within FN)	Local (within FN)
Mobile IP	$P \times N$	----	----
HAWAII	P	$P \times N$	$P \times K \times N$
Cellular IP	P	$P \times N$	$P \times K \times N$
TeleMIP	$P \times (N/R)$	$P \times N$	----

P: # of Mobile Nodes

N: # of Subnets

R: # of Subnets handled by a single MA

K: Average # of intermediate routers

Comparison

Desired Mobility Feature	Cellular IP	HAWAII	IDMP
Requires Minimal Changes to Domain Nodes	2	2	4
Efficient Address Utilization	5	2	5
Separate Security for Intra-Domain and Global Mobility	-	-	5
Reduces Intra-Domain Update Latency	5	3	5

Desired Mobility Feature	Cellular IP	HAWAII	IDMP
Reduces Global Update Frequency	5	5	5
Reduces Local Update Frequency	5	3	3
Low Encapsulation and Transport Overhead	4	4	2
Can Work without changes to CN	5	5	5

Desired Mobility Feature	Cellular IP	HAWAII	IDMP
Scalable Intra-Domain Routing	3	3	5
Well-defined for Arbitrary and Multi-Peered Networks	1	1	5
Multiple Agents for Dynamic Load Balancing	2	2	5
Supports Co-located Address Mode	–	5	5

5 (Most Favorable)

1 (Least Favorable)

Conclusions

- Micro-mobility (intra-domain mobility) management in wireless Internet is an important challenge.
- IDMP offers a two-level mobility management solution, as an adequate compromise between the need for fast intra-domain location updates and low network management complexity. Also does load balancing among MAs.
- Use of explicit locally-scoped address in IDMP promotes address efficiency and reduces the need for host-specific route management (as in Cellular IP or HAWAII).
- Stable care-of address promotes proper functioning of TCP applications and the establishment of backbone QoS bounds (up to the MA).
- IDMP supports fast handoff and efficient paging.
- Bandwidth Broker (BB) based architecture provides QoS support at only a nominal increase in the signaling cost, especially over the bandwidth-constrained wireless links.

Current and Future Work

- Explore the trade-off between multiple levels (more than two) hierarchy for intra-domain mobility management
- IDMP prototype development and extensive comparison with Cellular IP, HAWAII, HMIP, etc.
- Scalability study in IDMP QoS provisioning using Bandwidth Broker
- Resource reservation schemes using user profiles in IDMP based QoS framework
- Mobility management in wireless Internet using Software Agents

Internet Mobility Protocols

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Location-Based Services

Government Applications

- Safety: Police location, criminal tracking and navigation
- Protection: Firefighter location and navigation
- Health: Patient tracking, ambulance location, and navigation
- Emergency: E911, location of caller

Consumer Applications

- Automatic tracking : Tracking of children, pets, friends, parents, patients, phone, packages, nearest restaurants, nearest retailer, nearest bank, nearest ATM, etc.
- Road assistance (Automobiles with telematics navigation)
- Concierge services
- Mobile yellow pages
- Weather, Travel, Traffic information
- Personalized messaging and content services
- Identify who in buddy list is nearby
- City guide
- Collision notification
- Location Information Restriction (LIR)

Location-Based Services

Business Applications

- Enhanced call center
- Location based promotion coupons
- Tracking product inventory
- Tracking rental cars
- Tracking of stolen vehicles
- Supply/chain management
- Management of sales force, field service personnel
- Fleet management and dispatch
- Location sensitive billing
- Location targeted advertisements
- Location based customer service

Location Techniques

- ***Network-based (mobile assisted)***
  - Mobile provides position measurements to the network for computation of a location estimate by the network
  - Relatively expensive, entailing installation of additional hardware at each Base Station to monitor mobile handset transmissions & assist in the location process
- ***Mobile-based (network assisted)***
  - Require mobiles with GPS capabilities to measure and compute location
  - The network may provide assistance data to the mobile to enable location measurements or improve measurement performance or both

Location Techniques

- *Network based, mobile assisted*
  - Signal strength method
  - Angle of Arrival (AOA) method
  - Time of Arrival (TOA) method
  - Cell of Origin (COO) method
  - Time Difference of Arrival (TDOA) method
  - Observed Time Difference based (OTD, E-OTD) method
  - Assisted GPS (AGPS) method – mobile has GPS, sends measurements to network to compute location
  - Enhanced Forward Link Trilateration (EFLT)
  - Advanced Forward Link Trilateration (AFLT) – supports IS-801
- *Mobile based, network assisted*
  - Mobile has GPS, measure and compute location

Assisted GPS

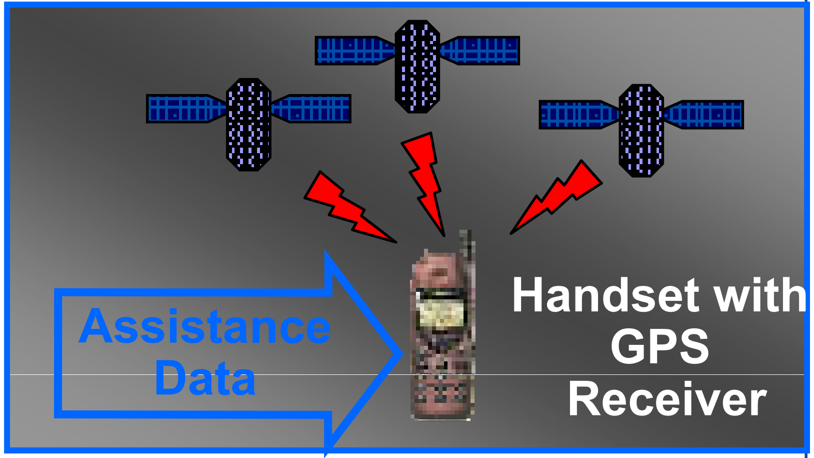
- **GPS is satellite based, existing location system**
- **GPS's main benefit is good accuracy: mean location error about 50 m with normal GPS**
- **Conventional GPS needs almost Line Of Sight to at least 3 satellites => does not work indoors or in urban canyons**

T1P1.5 uses three GPS variants:

- Conventional GPS (autonomous)

- GPS with assistance data from the network

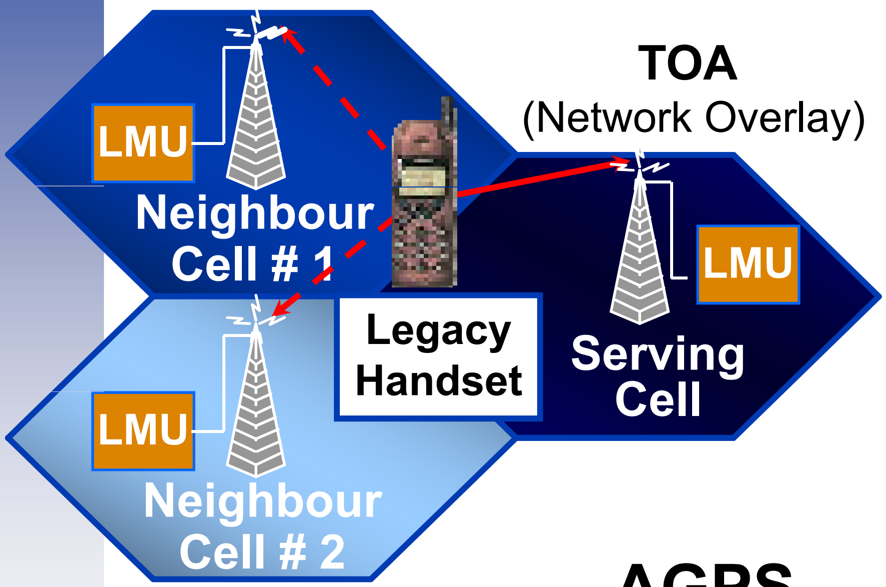
- GPS with assistance data from the network and position calculation in the network



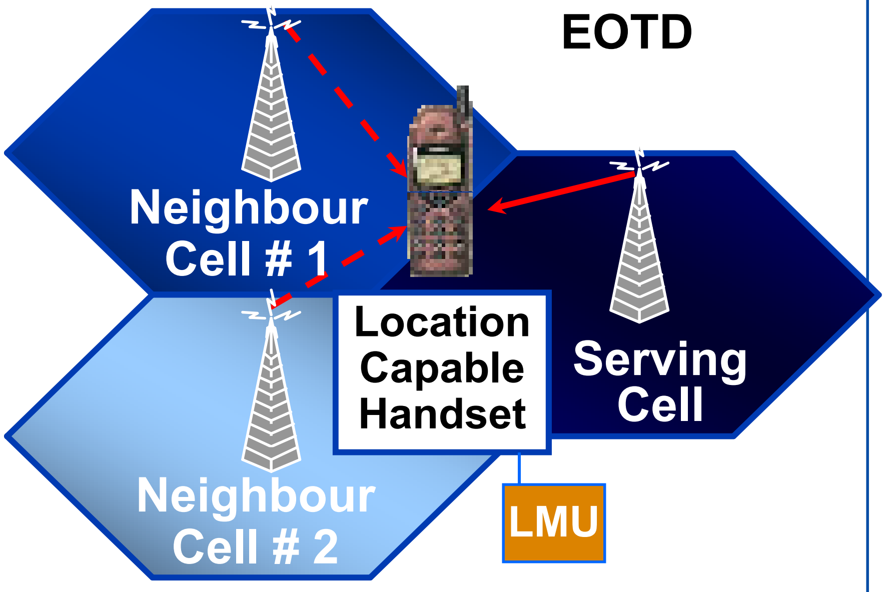
Location Techniques

TOA

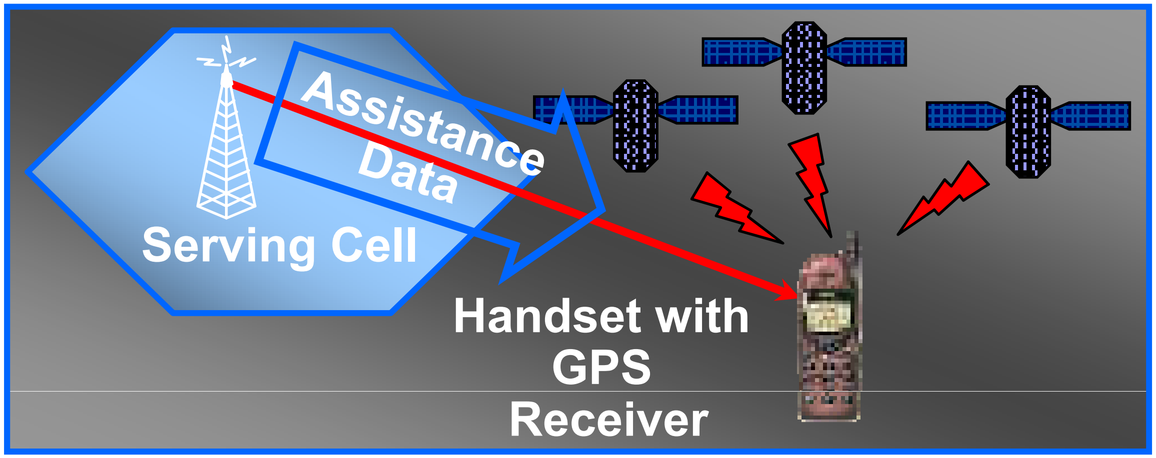
(Network Overlay)



EOTD



AGPS



- TOA: Time of Arrival
- E-OTD: Enhanced Observed Time Difference
- LMU: Location Measurement Unit
- GPS: Global Positioning System
- AGPS: Assisted GPS

Outline

- **June 18:**
  - Wireless Mobile Communications – Fundamentals
  - Cellular Network Concepts and Channel Access
  - Mobility Management and Wireless Internet
  - Resource Management and Wireless QoS
- **June 19:**
  - Wireless Sensor Networks (WSNs) – Fundamentals
  - Pervasive Computing and Cyber-Physical Systems
  - Energy-Efficient Algorithms and Protocols for WSNs
  - Security Solutions in WSNs
- **June 20:**
  - Smart Environments – Design and Modeling
  - Smart Healthcare – Middleware Services
  - Guidelines to Excellent Research
  - Mentoring and Value-Added Education

Lecture 6: Resource Management

- Wireless Multimedia Networks
- QoS Provisioning
- Call Admission Control
- Dynamic Resource Management
- References

Mobility Induced Challenges

- ☐ Resource (bandwidth, energy) Management
- ☐ Call / Service Admission Control
- ☐ Service Differentiation and End-to-End QoS
- ☐ Wireless Multimedia
- ☐ Addressing, Authentication, Security, Privacy
- ☐ Middleware Services and Applications
- ☐ Cross-Layer Optimization

What is Multimedia?

- Data of various types bundled as a single service: audio, video, text, images, …
- Bursty (VBR) or stream-oriented (CBR) traffic
- Elastic (not real-time): Telnet, ftp, http, e-mail
- Real-time: voice, video, telephony
- Lengthy and continuous load on the network
- Killer Applications
  - Traveler information systems (huge data transfer)
  - WWW browsing
  - Video and news on demand
  - Mobile office system
  - Stock market information, E-commerce
  - Telemedicine, Wearable health monitoring system

Characteristics of Multimedia Data

- Real time (delay sensitive): voice, audio, video
- Non-real time (delay tolerant): ftp, telnet, http, fax
- **Voice**
  - Continuous bit stream (CBR, VBR)
  - Can withstand error
  - Low bit-rate requirement (~ 9.6 – 19.2 Kbps)
- **Data**
  - Discontinuous packetized transmission
  - Usually non-resilient to errors
  - Variable (low-high) bit-rate requirement

Wireless Multimedia Networks

Objectives:

- Provide ubiquitous multimedia communication anytime
- Support the required *Quality of Service* (QoS)

Characteristics of Wireless Data:

- Varied QoS requirements (BER, bandwidth, delay, jitter)
- Synchronization of multiple data types and services
- Different (source) coding schemes for different applications
- Different error protection schemes (FEC, channel coding)
- Real-time error recovery (ARQ)

Wireless Multimedia Applications

Mobile Office

File Services
Real-time Support
Corporate Applications
Remote diagnostics/maintenance
Collaboration

E-Commerce

Broker Services
Electronic Ticketing
Online-banking
E-retail & Auction
Interactive Shopping

Communications

Messaging
Event notification
Email
Voice Services
Video Telephony

Entertainment

News, sports, weather updates
E-magazines
Interactive gaming
Audio on demand
Video on demand

Travel

Scheduling / Timetables
Navigation Services
Traffic Information
Directory Services
Tourist Services
Locator Services

Telemetry

Monitoring & Control
Data acquisition
Health monitoring
Surveillance

Core Technology Challenges

- Security / Privacy
  - Encryption / Authentication: Digital Signatures
  - IPSec for secure tunneling
  - SIM cards, smart cards, etc
- Quality of Service (QoS)
  - IntServ with RSVP
  - DiffServ
- IP Mobility
  - Mobile IP evolution
- High Performance Switching
  - MPLS for multimedia traffic
- TCP/IP Performance
  - Efficiency / performance for wireless access
- IP addressing
  - IPv6 for 128 bit addressing

What is QoS?

- Specified by *<bandwidth, delay, reliability>*
- Ability of a network element (e.g., an application, host or router) to have some level of assurance that its traffic and service requirements can be satisfied
- Predictable service for the traffic from the network

  e.g., CPU time, bandwidth, buffer space
- Acceptable end-to-end delay and minimum delay jitter
- End-to-end QoS

  - Requires cooperation of all network layers from top-to-bottom, as well as every network element

  - Knowledge of application at end points decides QoS functions implemented at every layer of the network protocol stack
- Type of Services
  - Best-effort: the Internet (lack of QoS)
  - Controlled load (soft QoS) : partial to some traffic but most effective
  - Guaranteed service (hard QoS) : absolute reservation of resources, more expensive

Wireless QoS Challenges

- Limited spectral bandwidth to be shared, causes interference; time varying communication links
- User mobility makes QoS provisioning complex because routes from source to destination cells are different, causing varying packet delays and delay jitters
- Error rate of wireless channel is higher due to mobility, interference from other media, and multi-path fading. So mobile hosts may experience different channel rates in the same or different cells
- Different QoS requirements for various types of applications: (9.6 Kbps for voice and 76.8Kbps for packetized video)

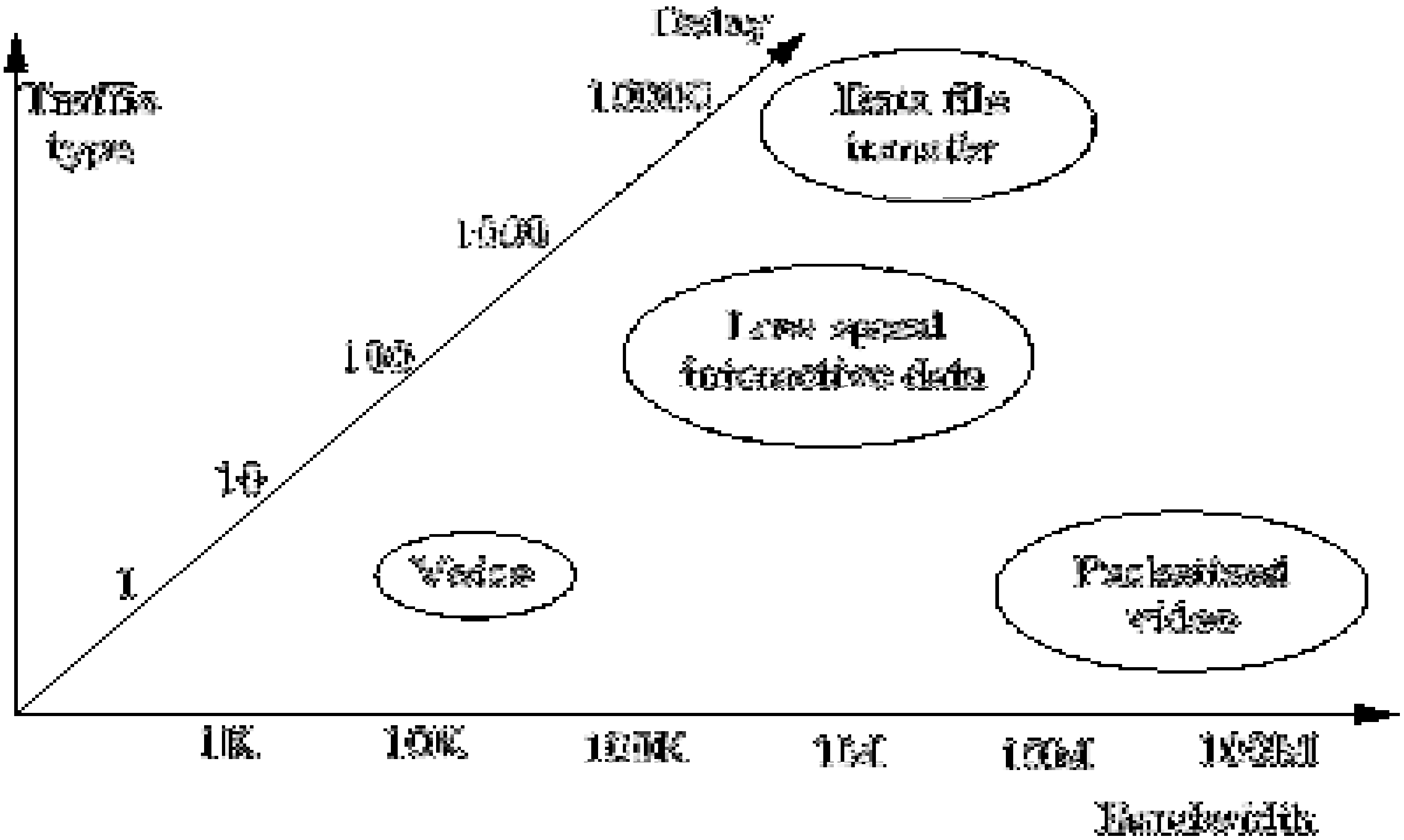
Wireless QoS: Desirable Features

- Adapt to dynamically changing network and traffic conditions
- Good performance for large networks and large number of connections (like the Internet)
- Higher data rate
- Modest buffer requirement
- Higher capacity utilization
- Low overhead in header bits/packet
- Low processing overhead/packet within network and end system

QoS Architecture

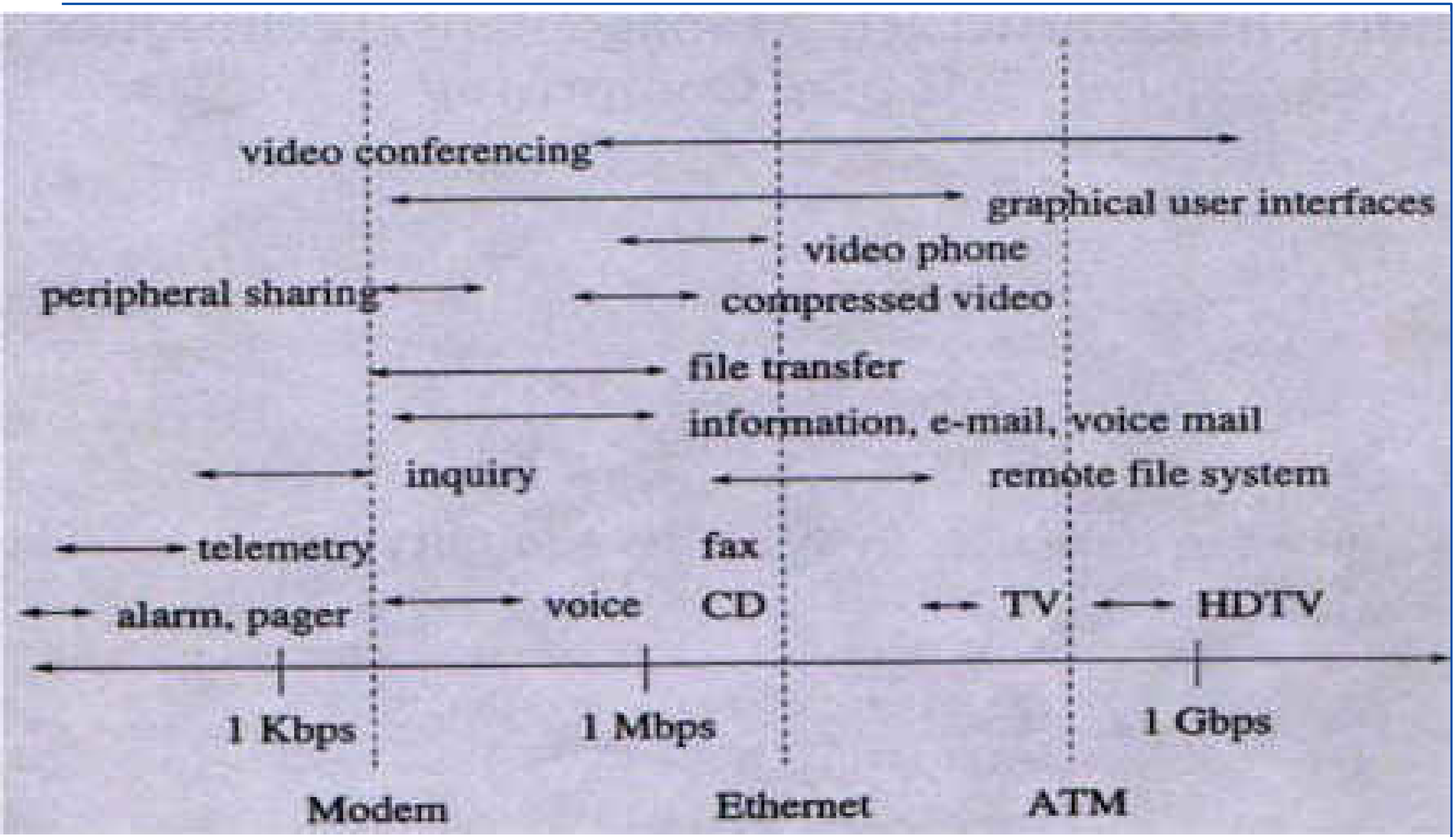
- Traffic Characterization
- Call Admission Control (CAC)
- Resource Management
- Packet Scheduling

Traffic Characteristics



- Existing mobile data networks offer very low transmission bandwidth, such as GPRS, cdma2000 1xRTT (56-144 Kbps)

Bandwidth Requirements



Application bandwidth requirements on log-scale axis in bits per second (bps)
Vertical dashed lines show the bandwidth capability of network technologies

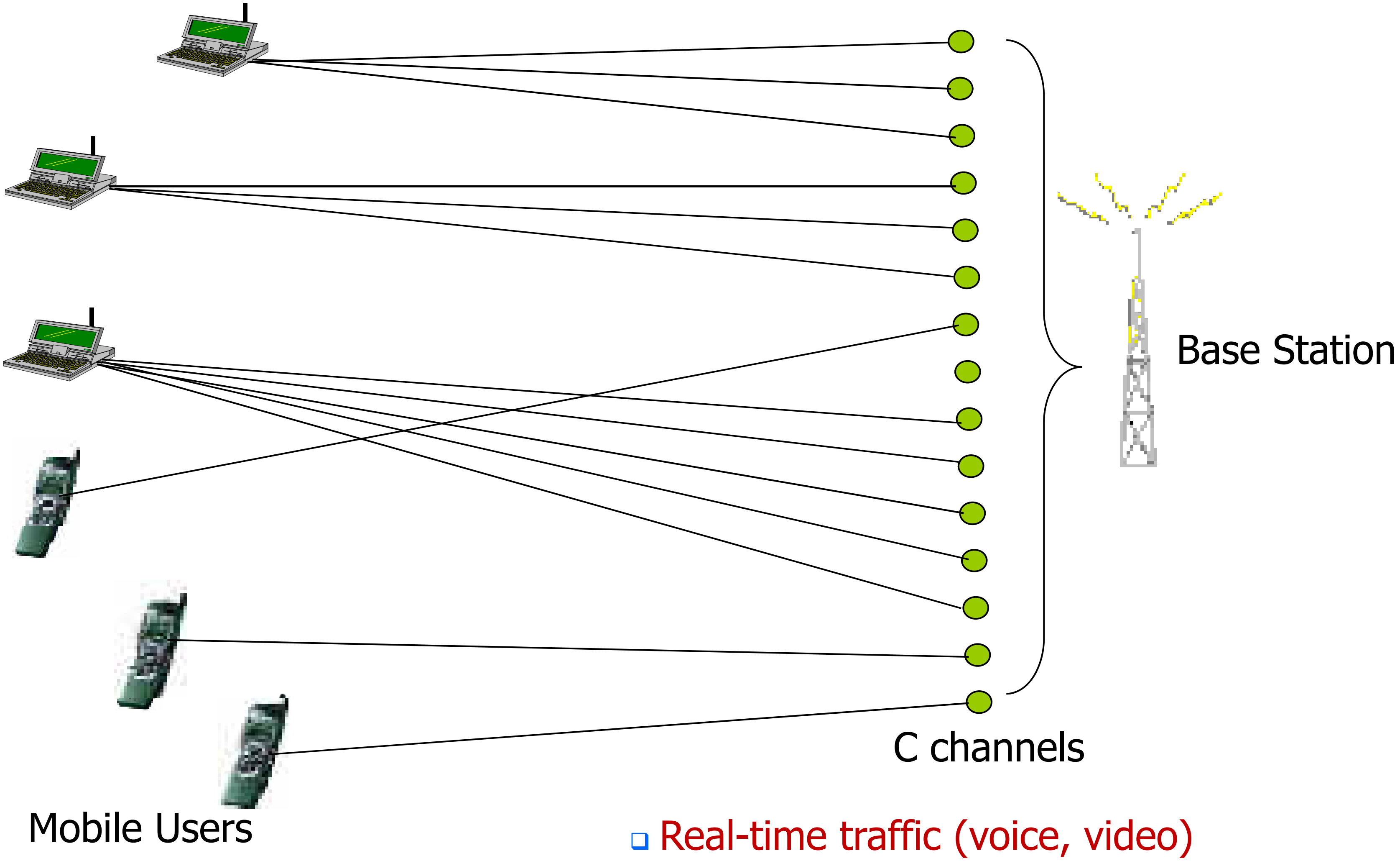
Mobility based Resource Reservation

- Shadow cluster concept
  - Well behaved users
  - The most likely cells to visit (prediction)
- Mobility support using multicasting in IP
  - Logging of Handoff
  - Forming a multicast group using the most likely cells
- Mobile extensions to RSVP
  - Active and passive reservation
  - Need for mobility specification
- Consensus?
  - Learn individual mobility profile and predict likely cells

Link Layer QoS

- Integrated (link and Network layers) QoS provisioning framework
- Link layer optimization by service differentiation between elastic and non-elastic traffic
- Wireless data packet fragmentation and dynamic scheduling based on degradability information
- Increased bandwidth utilization by
  - Optimistic reservation based on mobility prediction
  - Bandwidth compaction
  - Bandwidth stealing from higher to lower priority applications
  - Novel CAC/SAC to guarantee QoS

Multi-rate Traffic Scenario

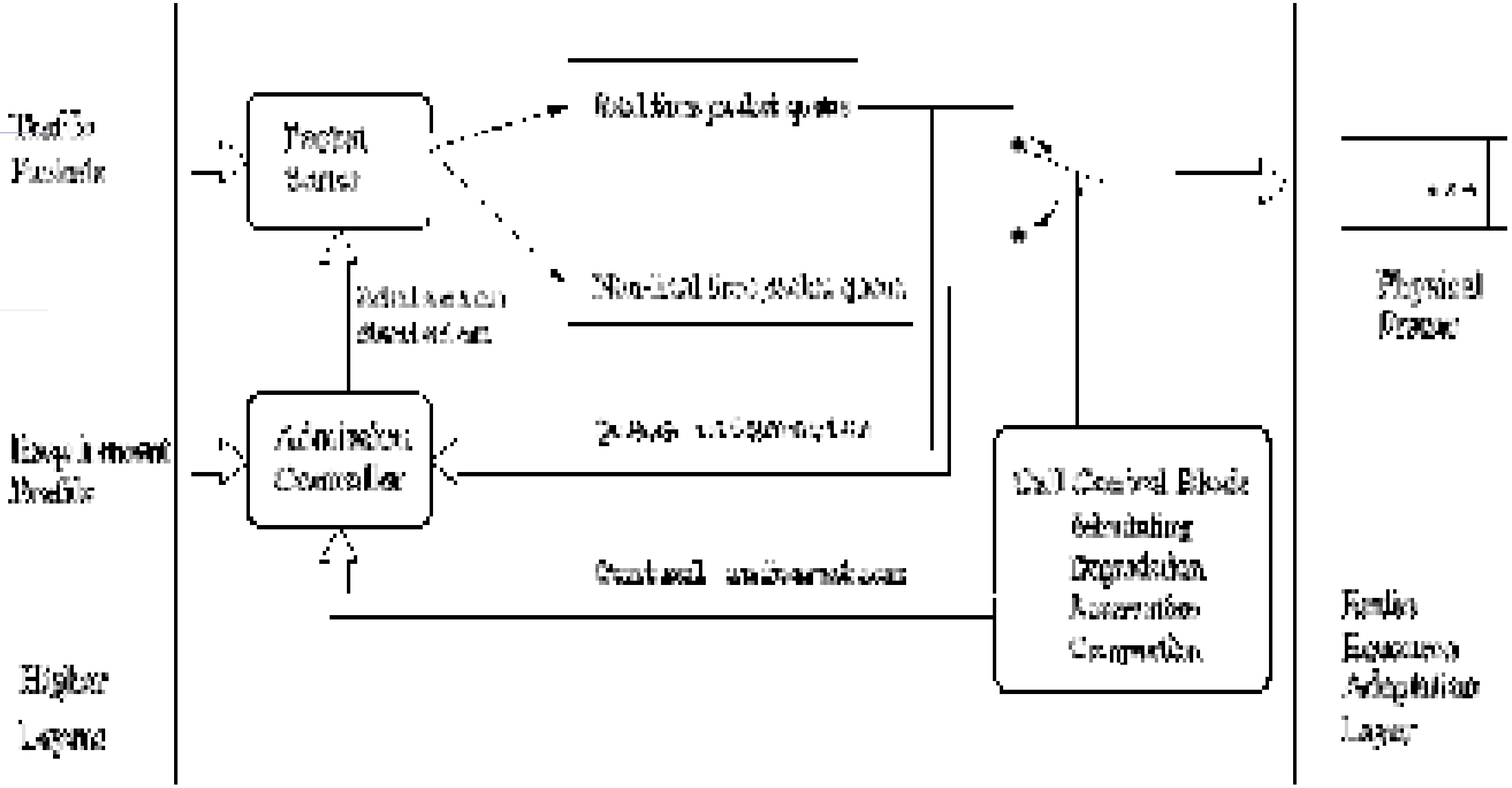


- Real-time traffic (voice, video)
- Non real-time traffic (TCP/IP packets)

Link Layer QoS Framework

- At call setup, higher layer application provides a **Requirement Profile** (RP) = <AB, MB, TYPE>
  - AB : average bandwidth required
  - MB : minimum bandwidth required
  - TYPE : elastic (not real-time) or inelastic (real-time)
- RP obtained from RSVP-like reservation setup signaling before accepting data flow into network
- **Session Admission Controller** decides on admitting a flow based on the RP and existing traffic conditions
- If the flow is admitted, the user RP is sent to the **Packet Sorter** for classification
- **Session Control Block** responsible for policy-driven schemes: bandwidth degradation, scheduling, compaction and stealing

Link Layer QoS Framework



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- Challenges and Preliminaries on Game Theory
- Cross-Layer Resource Management Framework

  - Network Layer Admission Control (Session Level)
    - Non-cooperative Game formulation
    - Establishment of Equilibrium
    - User Churn Rate Estimation

  - Link Layer Rate Control (Packet Level)
    - Differentiated QoS
    - CDMA Power Assignment Scheme
- Experimental Results

Dynamic Resource Management

H. Lin, S. K. Das, K. Basu, M. Chatterjee, “ARC: An Integrated Admission and Rate Control Framework for CDMA Data Networks Based on Non-cooperative Games,” *Proc. ACM Conf. on Mobile Computing & Wireless Networking (MobiCom)*, pp. 326-338, Sept 2003. Extended version in *IEEE Transactions on Mobile Computing*, Vol. 4, No. 3, pp. 243-258, 2005.

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    - CDMA Power Assignment Scheme
- Experimental Results

Driving Forces

- Seamless mobility in 3G cellular systems, IEEE 802.11 wireless LANs, etc.
- Growing demand for wireless Internet access
- Deregulation in wireless services and pricing → change from monopolistic to *competitive* market
- Need for efficient radio resource management (architectures, algorithms, protocols) for wireless data networks and multimedia services

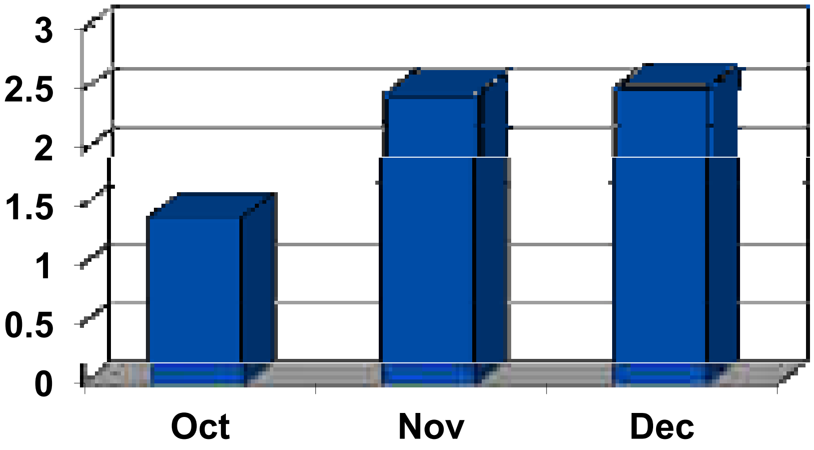
Challenges

- High competition among wireless data service providers
  - Customer has freedom to leave service providers (*churn*)
  - Customer-provider relationship: cooperative to non-cooperative
  - Customer satisfaction and expected QoS
  - Flexibility: Wireless Local Number Portability (WLNP)
- Churn is expensive
  - AT&T: 2.6% per month, about 30% per year
  - makes churn rate higher
  - Cost of churn

    = cost of getting a new subscriber

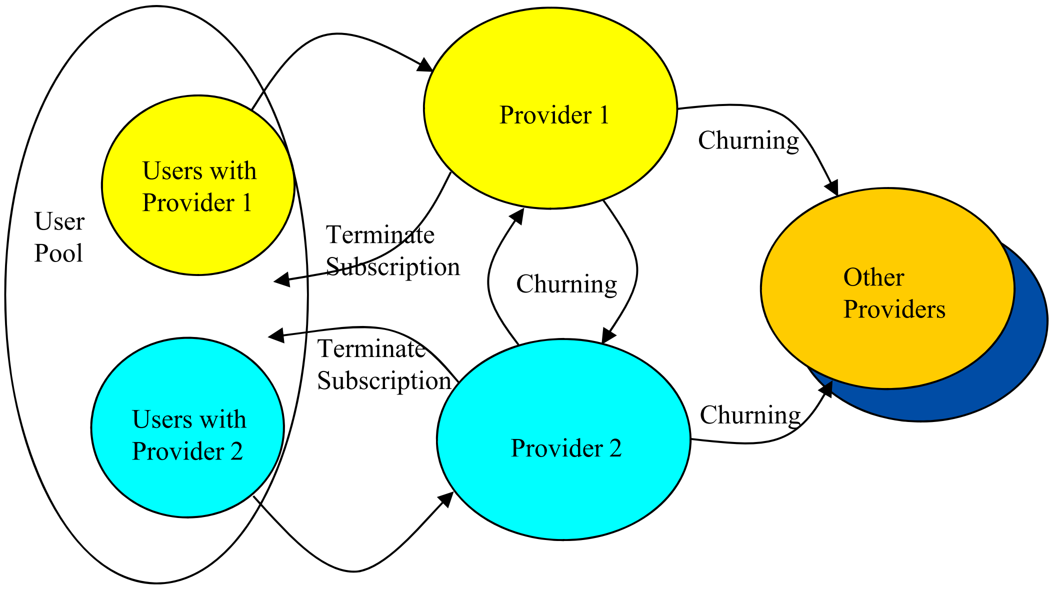
    = $377 on average

Monthly Churn Rate % (2012)



Challenges

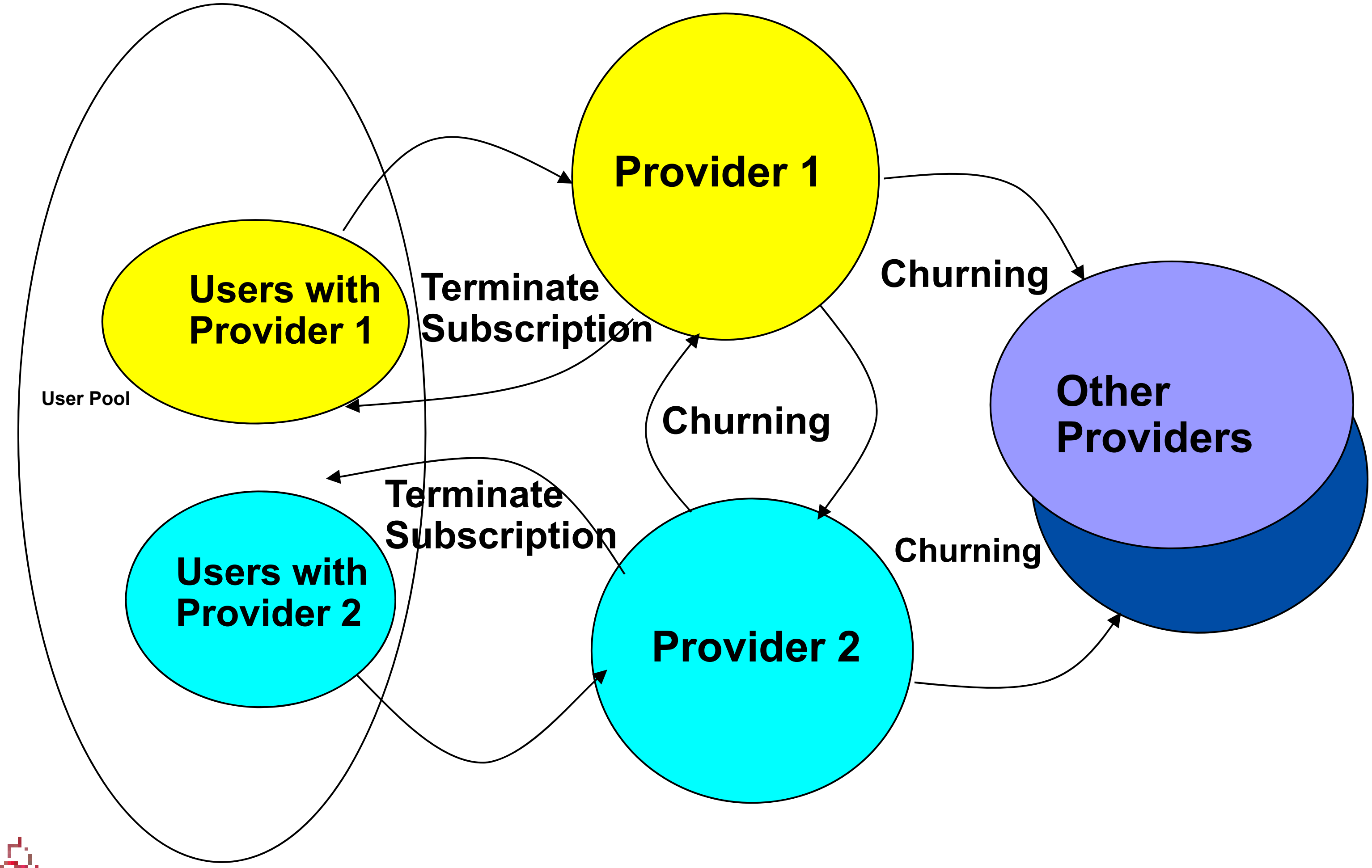
- Existing wireless resource management is based on monopolized market assumption
  - How to model churn behavior? The negative impact of churning on revenue could be hundreds of times larger in a competitive market than in the monopolized market



- Differentiated Quality of Service (QoS)
  - Different from voice networks, new resource management schemes required

Churning

- Users leaving the current service provider and subscribing to another provider



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Impact of Churn

- Factors influencing customer churning
  - Provider’s marketing ad and promotional packages
  - Network coverage, reliability, resource management policies
  - User utility: Perceived QoS, pricing, service features offered
- Churn is expensive: Major source of revenue loss
  - Churn rates in 2013 (Source: E&Y Partner)
    - 23% in UK, 21% in France, 14% in Germany, 33% in USA
  - Average cost of churn to service provider ~ $400 – $450
  - For 1 million customer base → $1 M

Objectives

- Model the complex relationship between customer churn behavior (due to competition) and wireless network design, management and operations
- Reduce churn rate or retain steady customer base
- Develop new paradigm for wireless resource management that incorporates conflicting utility:

Maximize revenue for providers & perceived QoS for users

- Design cross-layer resource management framework
  - Network layer admission control at session (macro) level
  - Link layer rate control at packet (micro) level
  - Physical layer power control in CDMA systems

Novel Contributions

- Paradigm shift from control theory to game theory
- Econometric model for wireless resource management. How to enhance customer satisfaction (differentiated QoS), reduce churn rate, improve provider's revenue?
- Admission control between service provider and user formulated as non-cooperative game with equilibrium(s)
- Adaptive resource allocation based on QoS tolerance in user utility
- Integrated Admission and Rate Control (ARC) framework for CDMA data networks

Problem Space

		Users	
		Single	**Multiple**
Service Providers	**Single**	**Trivial**	**Existing Work**
	Multiple	**Non-interesting**	**ARC Framework**

Basics of Game Theory

- A game consists of multiple players, each having a set of strategies with associated payoffs
- Cooperative and non-cooperative games
- Zero-sum and non-zero-sum games
- Bimatrix game: two-player game
- Pure and Mix strategy
  - Knowledge of opponent strategy known or not

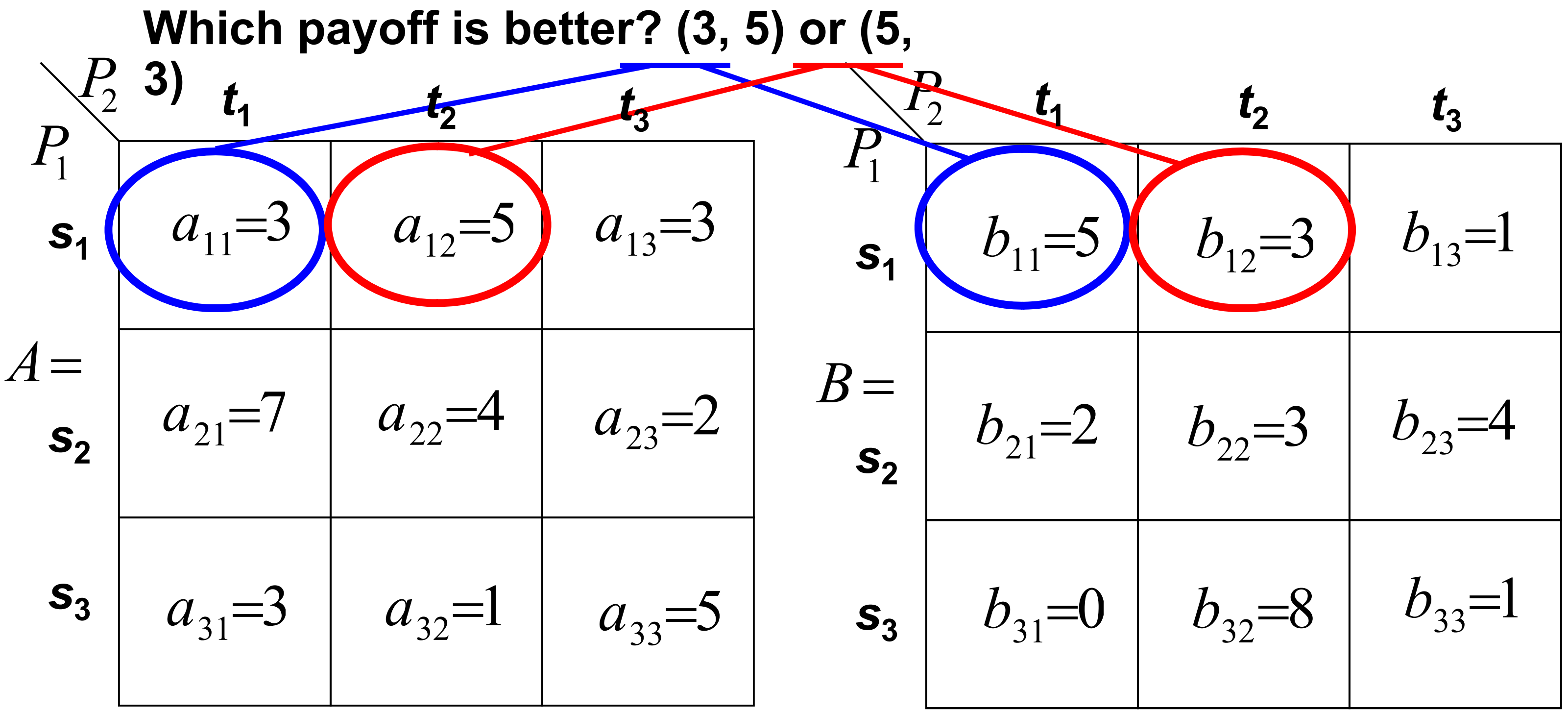
T. Basar and G. T. Olsder, Dyanmic Non-cooperative Game Theory, 2nd Ed., Society of Industrial and Applied Mathematics, 1999.

Bimatrix Games

- Strategies for players
  - P_1: $\{s_1, s_2, \ldots , s_m\}$
  - P_2: $\{t_1, t_2, \ldots, t_n\}$
- Payoff matrices of size m x n
  - $A = [a_{ij}]$, $B = [b_{ij}]$
  - a_{ij} : P_1 's payoff for if P_1 chooses strategy S_i, while P_2 chooses strategy t_j
  - b_{ij} : P_2's payoff if P_1 chooses S_i, while P_2 chooses t_j
- Goal: Players choose strategies to *optimize* payoffs
  → Outcome of a game is a pair of strategies

Best Strategy?

- Conflicting goals of players complicate “optimal” strategies for non-cooperative games



Which payoff is better? (3, 5) or (5, 3)

$$A = \begin{array}{c|ccc} P_1 \backslash P_2 & t_1 & t_2 & t_3 \\ \hline s_1 & a_{11}=3 & a_{12}=5 & a_{13}=3 \\ s_2 & a_{21}=7 & a_{22}=4 & a_{23}=2 \\ s_3 & a_{31}=3 & a_{32}=1 & a_{33}=5 \end{array}$$

$$B = \begin{array}{c|ccc} P_1 \backslash P_2 & t_1 & t_2 & t_3 \\ \hline s_1 & b_{11}=5 & b_{12}=3 & b_{13}=1 \\ s_2 & b_{21}=2 & b_{22}=3 & b_{23}=4 \\ s_3 & b_{31}=0 & b_{32}=8 & b_{33}=1 \end{array}$$

Nash Equilibrium

- A (stable) point where no player can improve payoff if other player do not change strategy

  → optimal solution

- A pair of strategies (s_{i^*} , t_{j^*}) constitutes non-cooperative *Nash Equilibrium* solution if :

$$a_{i^* j^*} \geq a_{i\, j^*} \quad \textbf{for all} \quad 1 \leq i \leq m$$

$$b_{i^* j^*} \geq b_{i^*\, j} \quad \textbf{for all} \quad 1 \leq j \leq n$$

assuming the goal of each player is to *maximize* payoff value

Nash Equilibrium (cont’d)

- Two Equilibriums (s_2, t_1) and (s_3, t_3)
- Outcome (a_{21}, b_{21}) = (3, 2) and (a_{33}, b_{33}) = (1, 3)

$$A = \begin{array}{c|ccc} P_1 \backslash P_2 & t_1 & t_2 & t_3 \\ \hline s_1 & 1 & 0 & -1 \\ s_2 & 3 & -1 & 0 \\ s_3 & 2 & 1 & 1 \end{array} \qquad B = \begin{array}{c|ccc} P_1 \backslash P_2 & t_1 & t_2 & t_3 \\ \hline s_1 & 1 & 0 & 1 \\ s_2 & 2 & -1 & 1 \\ s_3 & -1 & 0 & 3 \end{array}$$

Dominant and Dominated Strategy

- In a bimatrix game, for player P_1, strategy S_i dominates strategy S_k if

$$a_{ij} \geq a_{kj}, \text{ for all } \; j = 1, \ldots, m$$

- S_i and S_k *are* *dominant* and *dominated* strategies for P_1.
- Selecting a dominant strategy is as good as selecting the dominated strategy. So, finding Equilibrium for a game, the dominated strategy can be safely removed.

Dominating Strategy

$$A = \begin{array}{c|ccc} P_1 \backslash P_2 & t_1 & t_2 & t_3 \\ \hline s_1 & 1 & 0 & -1 \\ s_2 & 3 & -1 & 0 \\ s_3 & 4 & 1 & 1 \end{array}$$

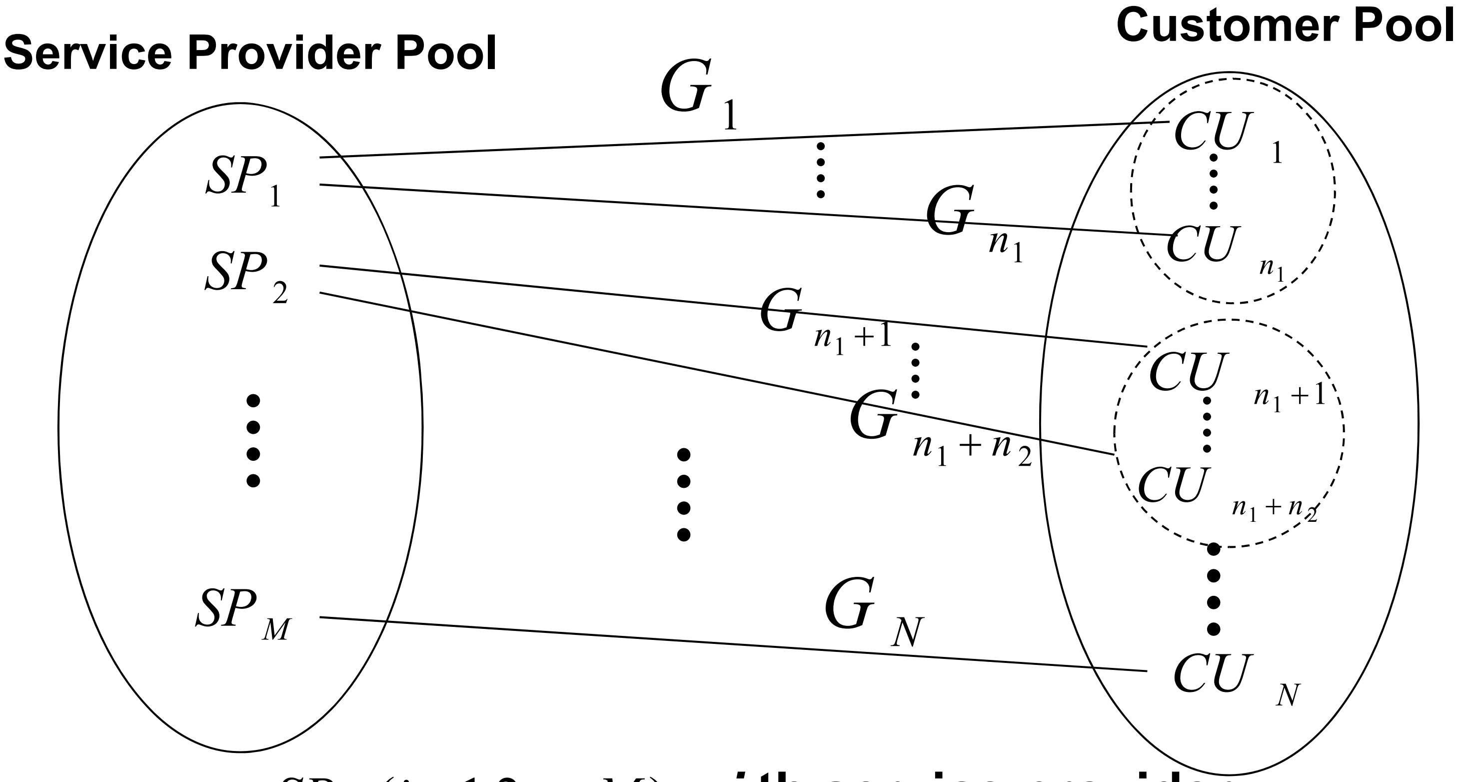
$$B = \begin{array}{c|ccc} P_1 \backslash P_2 & t_1 & t_2 & t_3 \\ \hline & 1 & 0 & 1 \\ & 2 & -1 & 1 \\ & -1 & 0 & 3 \end{array}$$

s_2: Dominated strategy for P_1

s_3: Dominating strategy for P_1

Service Provider Vs. User Game

- A user associated with *only* one provider at a time
- Interactions between service providers and users can be modeled as *N* two-player games (G_1, G_2, …, G_N)



$SP_i \ (i=1,2,...,M)$ **:** ***i*** **th service provider**

$CU_j \ (j=1,2,...,N)$ **:** ***j*** **th customer**

Admission Control Game

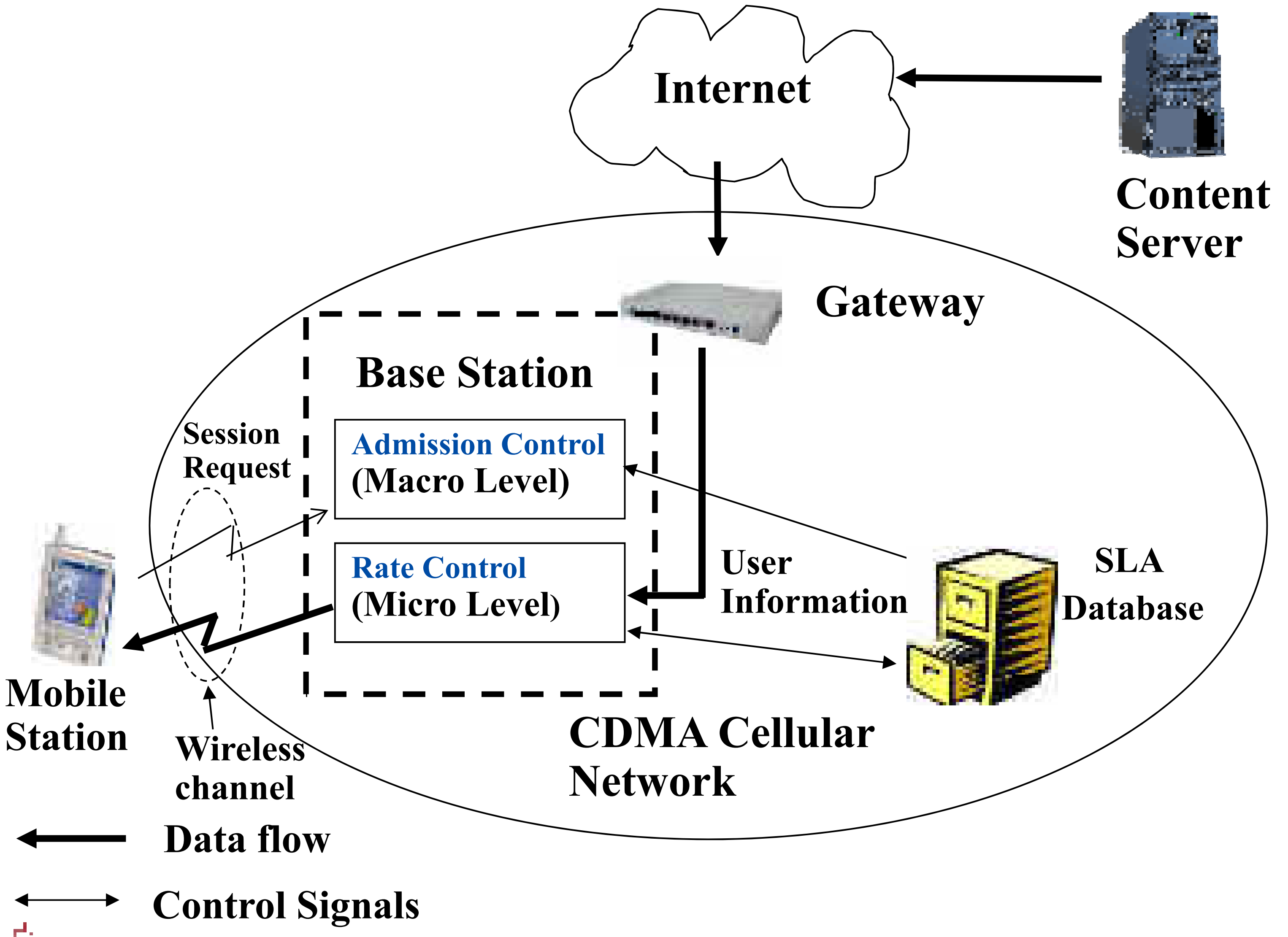
- Non-cooperative, non-zero-sum game
  - *Service provider's utility:* Revenue generation
  - *Customer's utility:* QoS satisfaction
- *One-by-one* admission control mode : one game instance played when a new session request comes to the system
- *Batch mode*: Multiple session requests buffered and processed in batches → *n*-player game

Network Model

- CDMA air-interface
- Multiple users can receive downlink traffic simultaneously with different CDMA codes
- *Differentiated Service: K* classes of users

  (the smaller the number, the higher the priority)
- User classes are prioritized in terms of call blocking rate and actual power budget allocated
  - Power decides on QoS in CDMA networks

ARC Framework



Game Formulation

- Strategy Sets:
  - Service Provider: {SS_1, SS_2}
    - SS_1: admit the request
    - SS_2: reject the request
  - User seeking admission: {CS_1, CS_2}
    - CS_1: leave the current provider
    - CS_2: stay with the current provider

Payoff for Service Provider

$A =$

Service Provider \ Customer	**CS$_1$: Leave provider**	**CS$_2$: Stay with provider**
SS$_1$: Admit	$U + C_k - F - L_k$	$U + C_k - F$
SS$_2$:Reject	$U - L_k$	U

U : revenue earned from all on-going sessions

C_k : revenue gain for admitting new session (class k)

L_k : revenue loss due to churn of user seeking admission

$R_i(.)$: class-*i* user churn rate as a function of packet blocking rate, Pb_i

$$F = \sum_{i=k}^{K} N_i R_i(Pb_i) L_i$$

Revenue loss due to churning of users in the same or lower priority than class-*k* user admitted

Payoff Matrix for Customer

$$B = \begin{array}{c|c|c} \text{Service Provider} \backslash \text{Customer} & CS_1\text{: Leave provider} & CS_2\text{: Stay with provider} \\ \hline SS_1\text{: Admit} & w_1(U_k(Pb_k)+W_a)-w_2L_c & U_k(Pb_k)+w_a \\ \hline SS_2\text{ : Reject} & w_b - w_2L_c & w_b \end{array}$$

$U_k(.)$: Class-*k* user utility as a function of Pb_k

$w_{a,}$ w_b : User utility when the request is admitted or blocked (rejected)

w_1, w_2 : Weights for user preference on money saving or satisfaction optimization ($w_1 + w_2 = 1$)

Find Equilibrium

- Case 1 (under-loaded system): Admitting a new request does not affect QoS of existing customers

$$Pb_i = 0 \;\Rightarrow\; R_i(Pb_i) = 0, \text{ for all } 1 \le i \le K$$

- Assumptions:

- User churning is only caused by unsatisfied QoS

- Churn rate is a function of packet blocking rate, Pb_i

Equilibrium (Case 1)

$$A = \begin{array}{c|c|c} & \mathbf{CS_1} & \mathbf{CS_2} \\ \hline \mathbf{SS_1} & U+C_k-\cancel{F}-L_k & U+C_k-\cancel{F} \\ \hline \mathbf{SS_2} & U-L_k & U \end{array}$$

$$B = \begin{array}{|c|c|} \hline w_1U_k(Pb_k)+w_a-w_2L_c & U_k(Pb_k)+w_a \\ \hline w_b-w_2L_c & w_b \\ \hline \end{array}$$

$$\left. \begin{array}{l} F = \sum_{i=k}^{K} N_i R_i(Pb_i) L_i \\ R_i(Pb_i) = 0 \end{array} \right\} \Rightarrow F = 0$$

Equilibrium (Case 1)

$$A = \begin{array}{c|cc} & CS_1 & CS_2 \\ \hline SS_1 & U+C_k-L_k & \boxed{U+C_k} \\ SS_2 & U-L_k & U \end{array}$$

$$B = \begin{bmatrix} w_1U_k(Pb_k)+w_a-w_2L_c & \boxed{U_k(Pb_k)+w_a} \\ w_b-w_2L_c & w_b \end{bmatrix}$$

Equilibrium point: (SS_1, CS_2)

Win-win strategy: service provider admits new request and user stays with current provider

Find Equilibrium (Case 2)

- Case 2 (Fully loaded system): Packet blocking probability not all zero,

$$\exists i, \text{such that } Pb_i \neq 0, (1 \leq i \leq K) \Rightarrow R_i(Pb_i) \neq 0$$

$$F = \sum_{i=k}^{K} N_i R_i(Pb_i) L_i \neq 0$$

- Equilibria determined by relative values of revenue gain (C_k) for admitting the new class-*k* user Vs. potential revenue loss (*F*) from other users whose services got affected by the admitting this user

- $C_k > F$ ➔ Admit the request, otherwise reject it

Find Equilibrium (Case 2)

- Subcase 1: If $C_k > F$

$$A = \begin{array}{c|c|c} & \mathbf{CS_1} & \mathbf{CS_2} \\ \hline \mathbf{SS_1} & U+C_k-F-L_k & U+C_k-F \\ \hline \mathbf{SS_2} & \overset{>}{U-L_k} & \overset{>}{U} \end{array}$$

$$B = \begin{array}{|c|c|} \hline w_1U_k(Pb_k)+w_a-w_2L_c & U_k(Pb_k)+w_a \\ \hline w_b-w_2L_c & w_b \\ \hline \end{array}$$

Dominant strategy: SS_1

Find Equilibrium (Case 2)

- Subcase 2: If $C_k < F$

$$A = \begin{array}{c|cc} & CS_1 & CS_2 \\ \hline SS_1 & U+C_k-F-L_k & U+C_k-F \\ SS_2 & \overset{<}{U-L_k} & \overset{<}{U} \end{array}$$

$$B = \begin{array}{|c|c|} \hline w_1U_k(Pb_k)+w_a-w_2L_c & U_k(Pb_k)+w_a \\ \hline w_b-w_2L_c & w_b \\ \hline \end{array}$$

Dominant strategy: SS_2

Admission Control: Batch Mode

- Process one request at a time

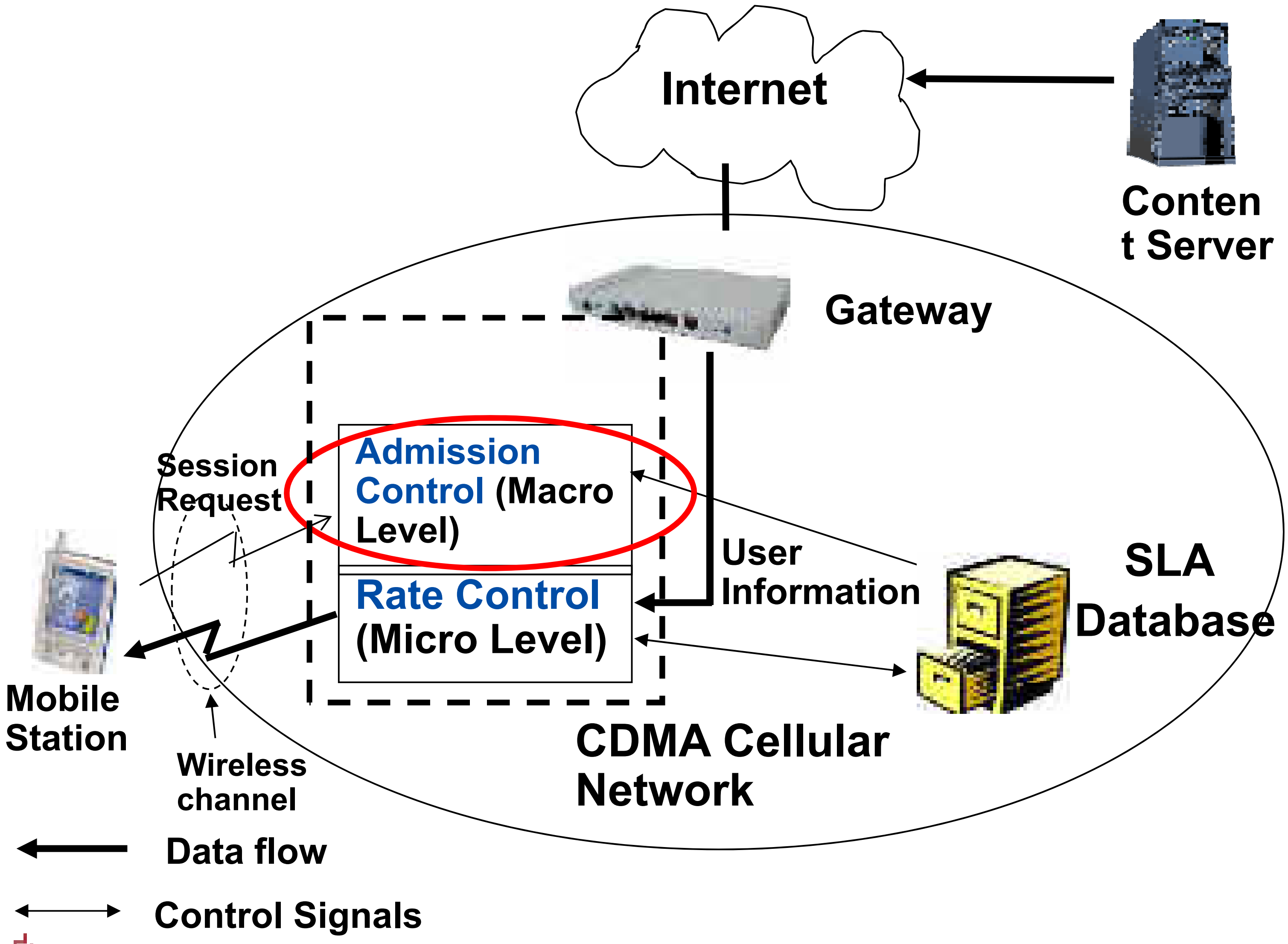
1. Evaluate payoffs based on QoS measurements and user information from SLA database

2. Make decisions according to the equilibrium condition and dominant strategies

  - The game has either an equilibrium or a dominant strategy for the service provider

    ➔ Admission policy is clearly defined

ARC Framework



Internet

Content Server

Gateway

Admission Control (Macro Level)

Rate Control (Micro Level)

User Information

SLA Database

Session Request

Mobile Station

Wireless channel

CDMA Cellular Network

Data flow

Control Signals

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User Churn Rate

- *Churn*: probability that a class-*i* user leaves a provider
- Depends on (subjective) satisfaction of user QoS
- *Churn rate* of class-*i* user:

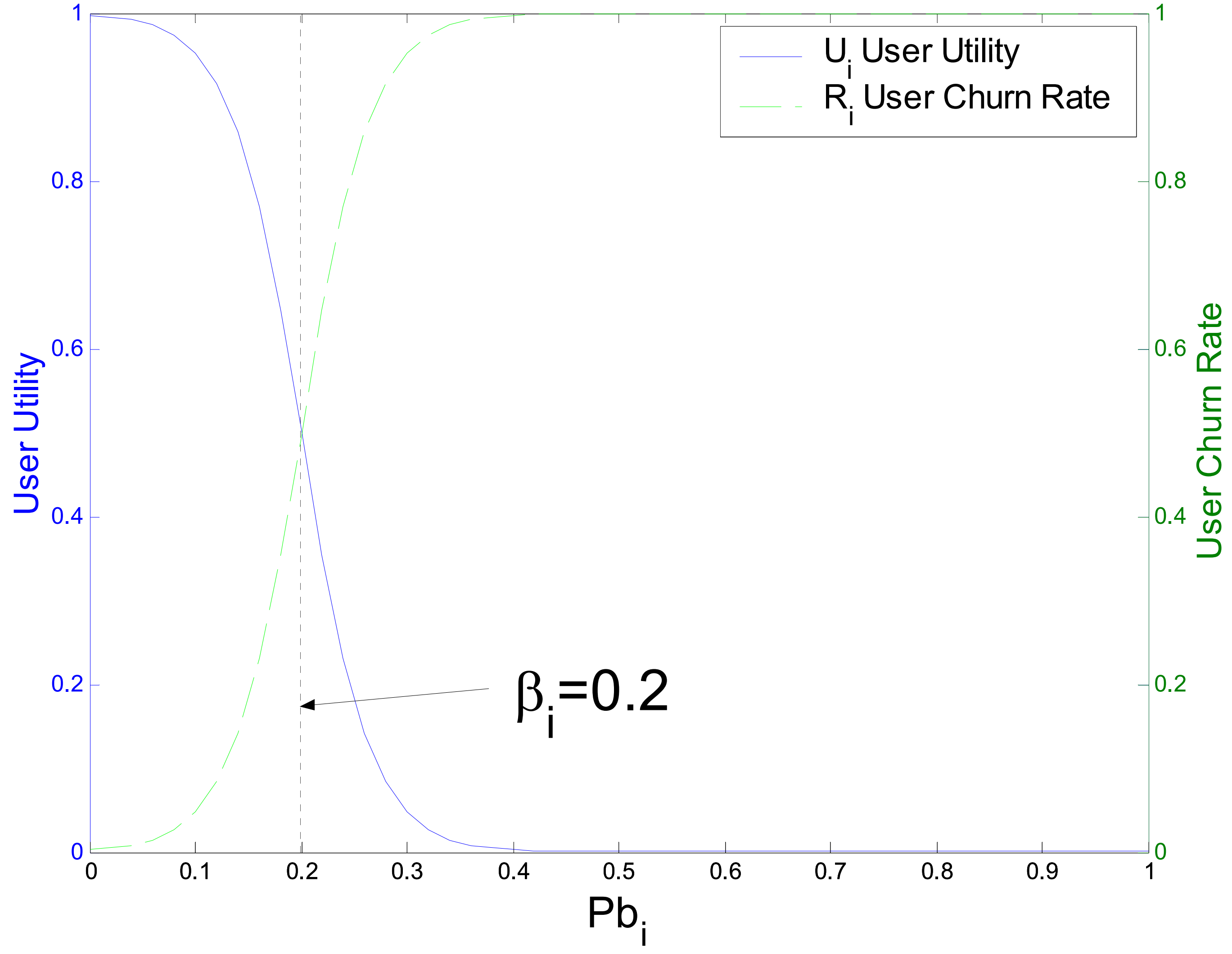
$$R_i(U_i) = 1 - U_i(Pb_i)$$

- User utility, $U_i(Pb_i)$, assumed as Sigmoid Function

$$U_i(Pb_i) = \frac{1}{1 + e^{-\alpha_i(\beta_i - Pb_i)}}$$

Parameters α_i and β_i can be tuned to achieve customized utility function for different users

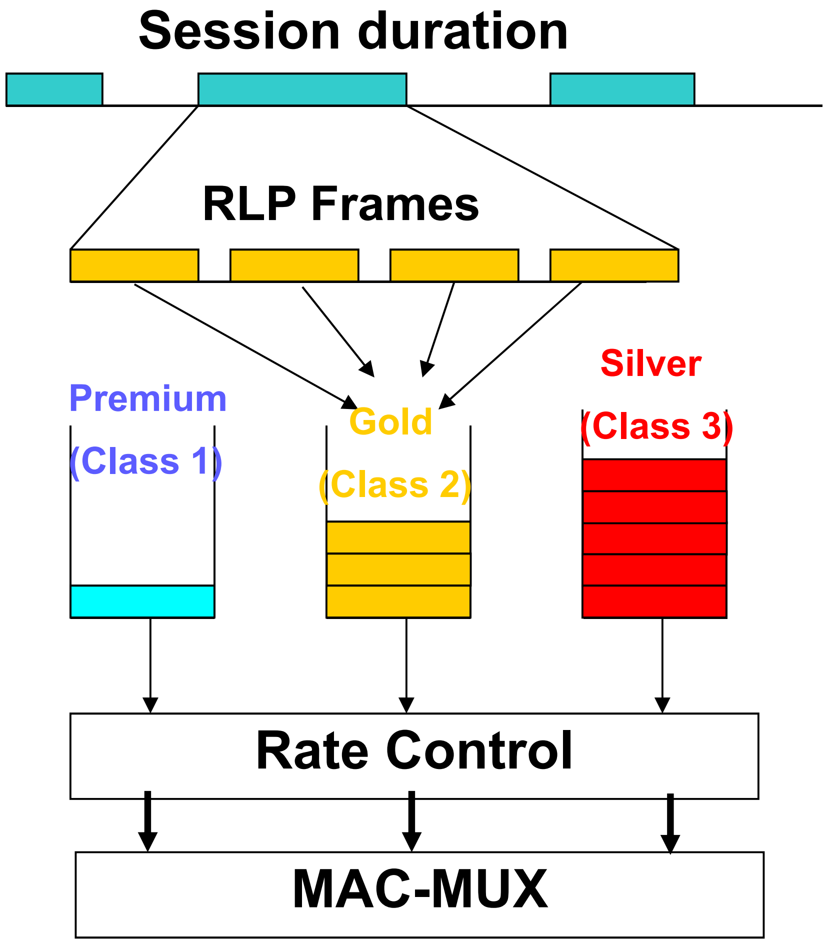
Churn Rate Estimation



β_i **: user's expected QoS**

α_i **: user's tolerance to QoS degradation**

Dynamic Rate Control



If power budget does not allow full rate transmissions for all users, lower class users are deprived in order to satisfy power of higher class users → Differentiated QoS

Rate Control Example

- Premium (class-1), Gold (class-2), Silver (class-3)

  N_i : number of class-*i* users currently in the system

  P_M : maximum transmission power supported by CDMA base station (downlink is power limited)

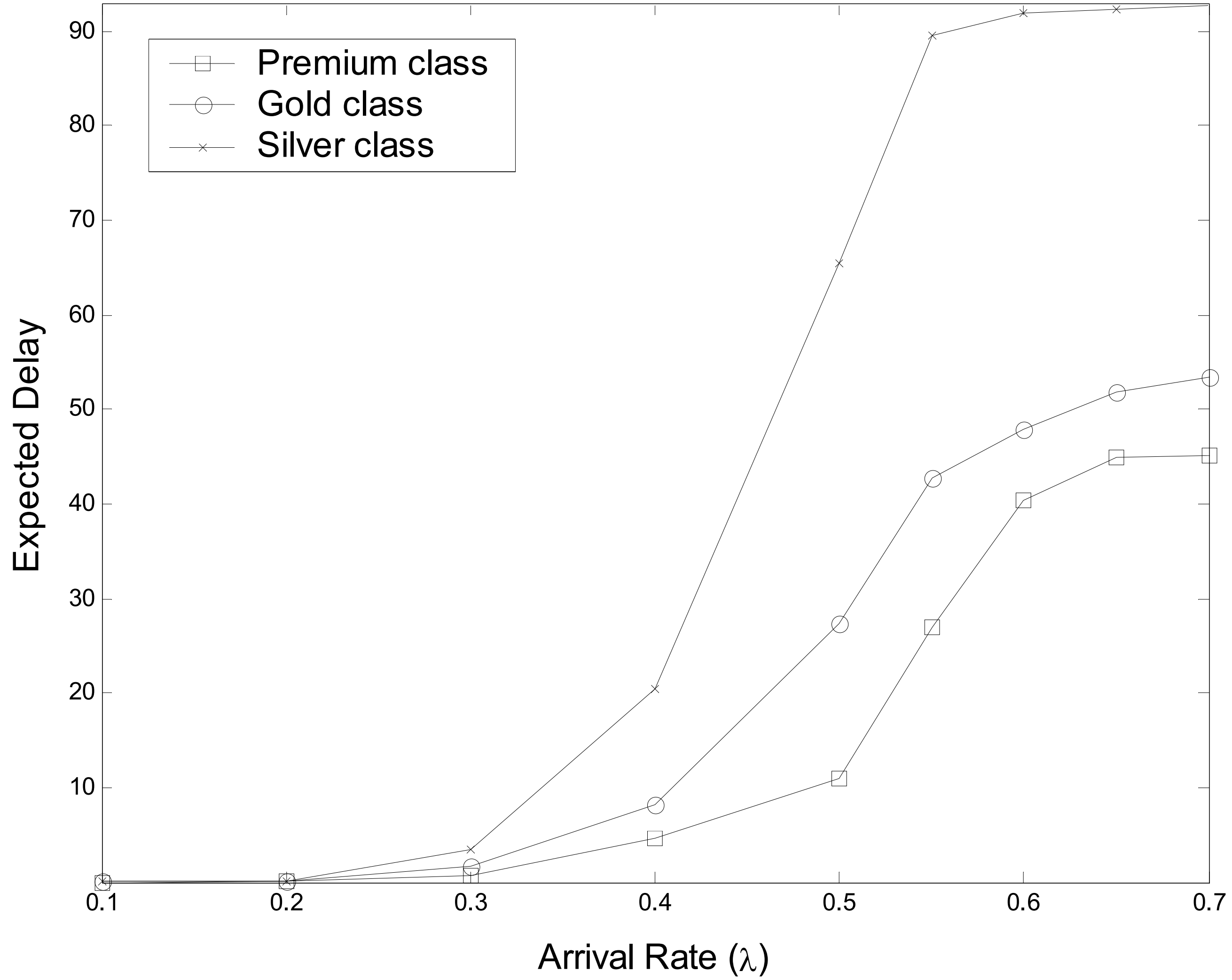
  $\overline{P_i}$: average power per class-*i* user

- Power Deficiency : $D = N_1\overline{P_1} + N_2\overline{P_2} + N_3\overline{P_3} - P_M$
- Reduce power budget for class-2 and class-3 users:

$$Pt_2 = N_2\overline{P_2} - \gamma D \qquad Pt_3 = N_3\overline{P_3} - (1-\gamma)D$$

- Reduced power budget → base station uses lower rate for class-2 and class-3 users

Simulation Results: Delay



- **Premium class has lowest delay, Silver has the highest → Differentiated QoS**

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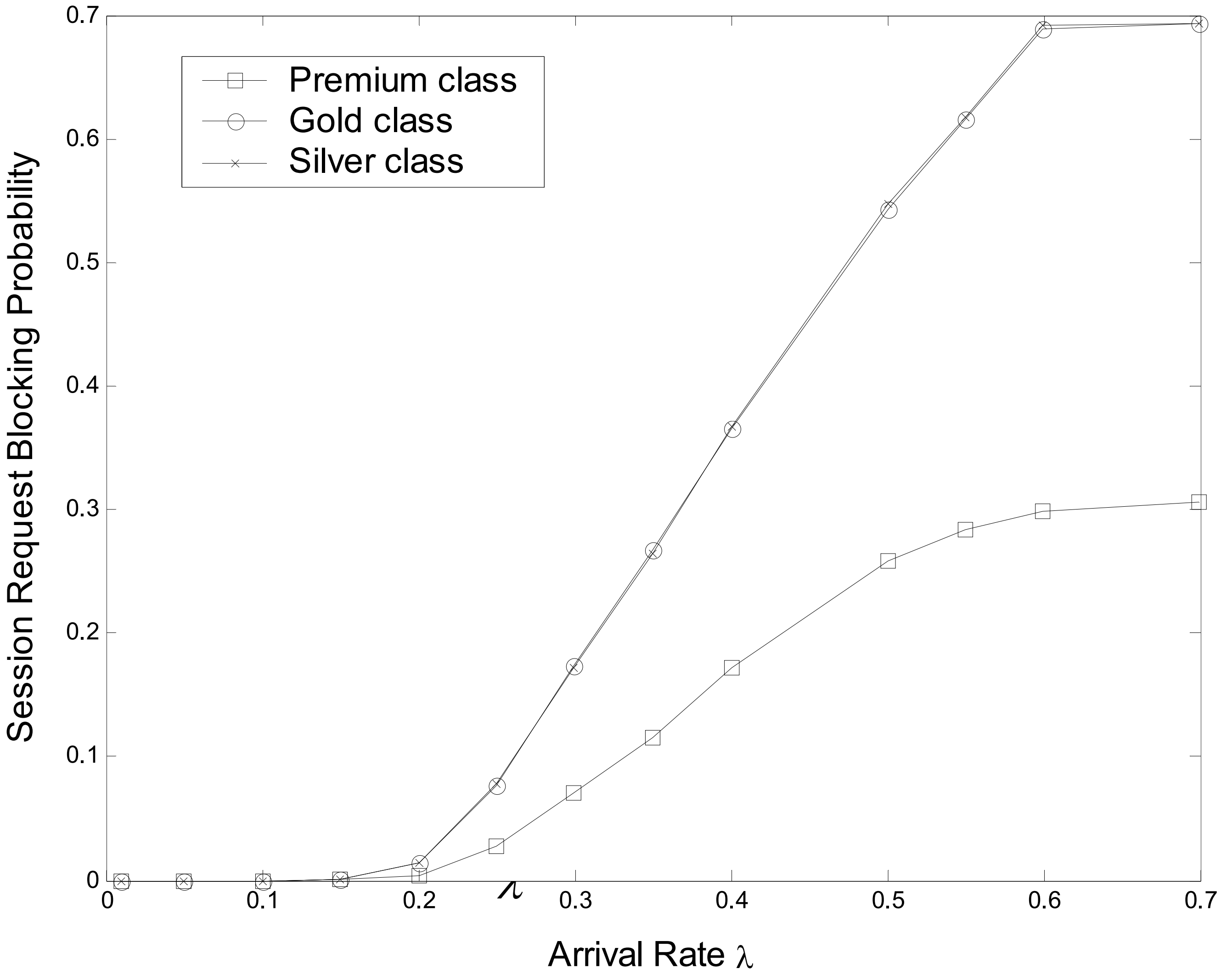
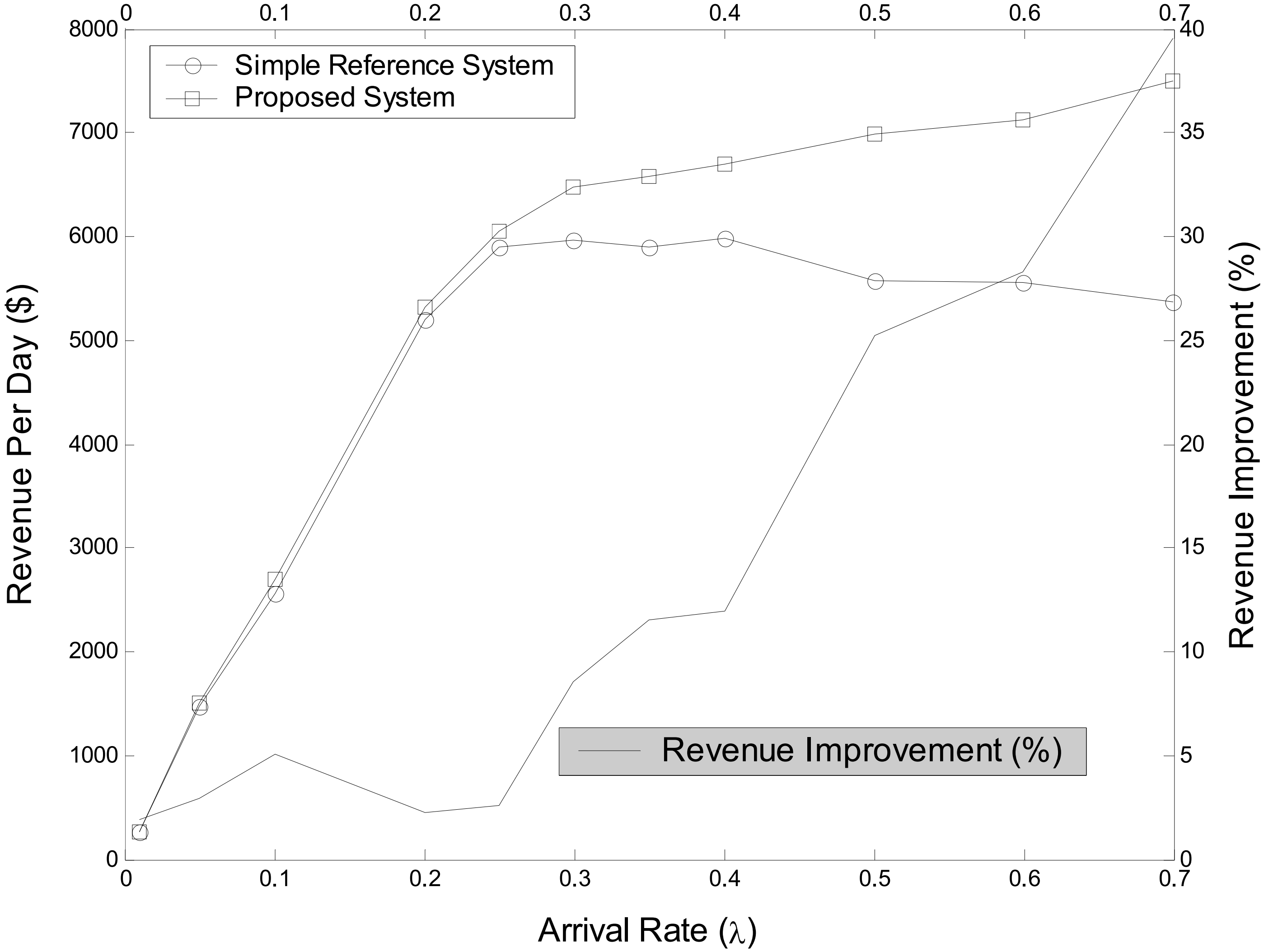
Blocking Rate



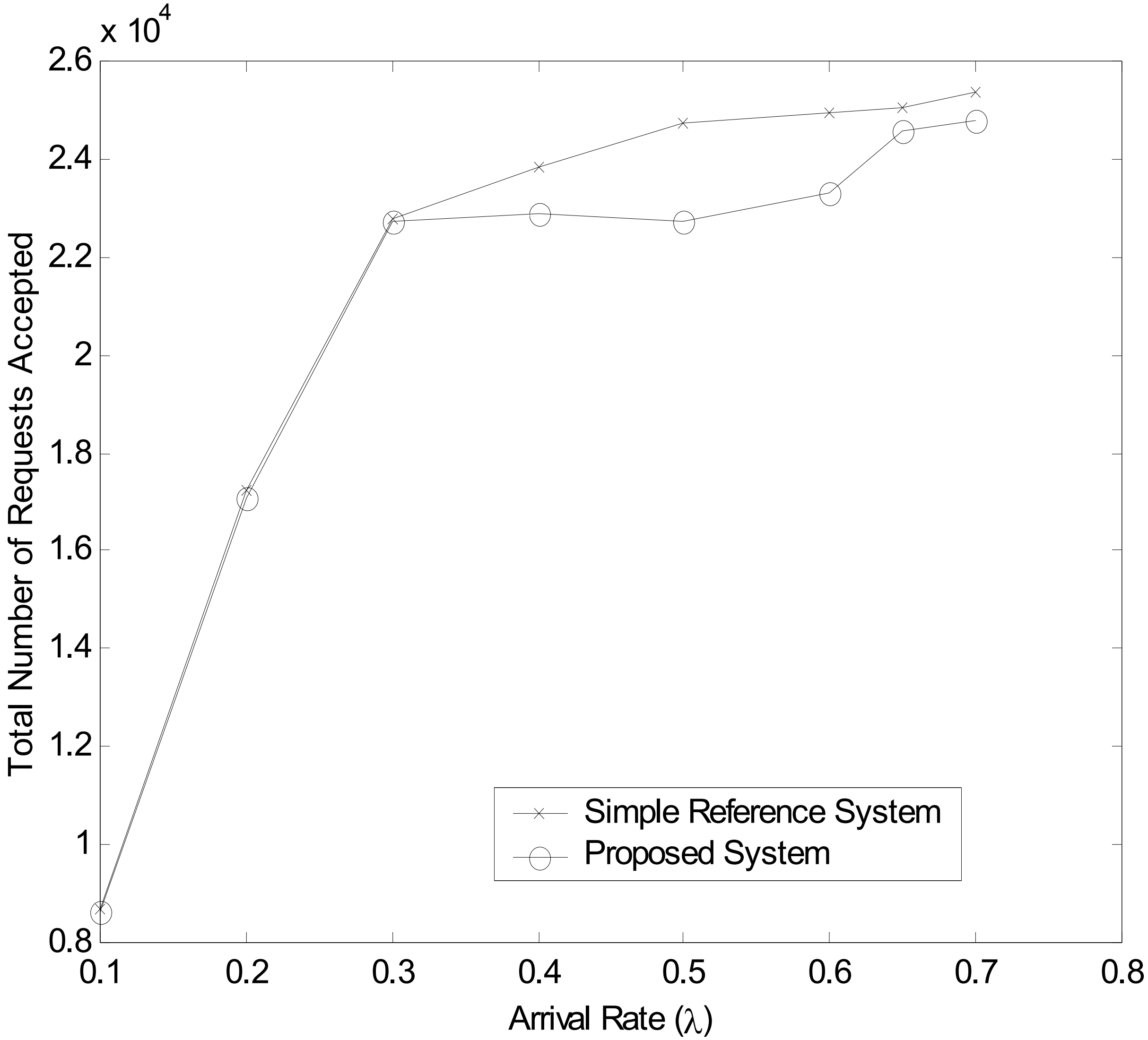
- **Premium class has much lower blocking rate than Gold and Silver Classes**

Revenue Improvement



- **ARC generates higher revenue than reference system for loaded networks**

Throughput



Total Accepted Requests vs. λ

Conclusions

- Admission control in a competitive wireless data network is modeled as a non-cooperative game between service providers and users
- By formulating competitiveness (in the form of user churn rate) into service provider's utility, the ARC framework maximizes revenue
- It also achieves differentiated QoS in terms of session request blocking rate and packet delay
- Multi-player game admission (batch mode) generates more revenue than 2-player (one-by-one mode)

Future Work

- Extend game model to accommodate multiple threshold based strategies for users and service providers in admission and/or rate control schemes
- Design more sophisticated, game-theoretic (CDMA) power control algorithm to integrate physical, link and network layer solutions
- Incorporate session handoff requests into ARC framework → Mobility-aware resource management

Refs. on Resource Management

- H. Lin, M. Chatterjee, S. K. Das and K. Basu, "ARC: An Integrated Admission and Rate Control Framework for Competitive Wireless CDMA Data Networks Using Non-Cooperative Games," *IEEE Transactions on Mobile Computing*, Vol. 4, No. 3, pp. 243-258, May/June 2005. (Also Proc. ACM Mobicom'03)
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Outline

- **June 18:**
  - Wireless Mobile Communications – Fundamentals
  - Cellular Network Concepts
  - Wireless Networks – Mobility Management
  - Wireless Networks – Resource Management
- **June 19:**
  - Wireless Sensor Networks (WSNs) – Fundamentals
  - Energy-Efficient Algorithms and Protocols for WSNs
  - Pervasive Computing & Cyber-Physical Systems
  - Security Solutions in WSNs
- **June 20:**
  - Smart Environments – Design and Modeling
  - Smart Healthcare – Middleware Services
  - Guidelines to Excellent Research
  - Mentoring and Value-Added Education

Sensing the Physical World

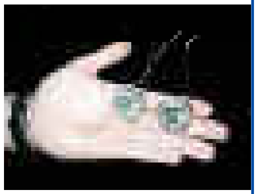
We live in a physical world, which we need to understand, serve, and control

Monitoring

- Agriculture
- Border Surveillance
- Ecosystem
- Environment
- Habitat
- Health, Wellbeing
- Infrastructure

Wireless Sensors

Sensor node Architecture



Computation

In-network Processing:

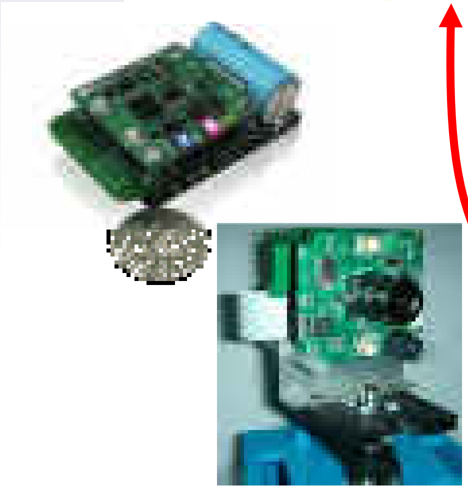
Fusion, Estimation, Filtering, Aggregation

Communication

(Wireless)

Transmission/Reception:

Broadcasting, Routing, Dissemination



Control

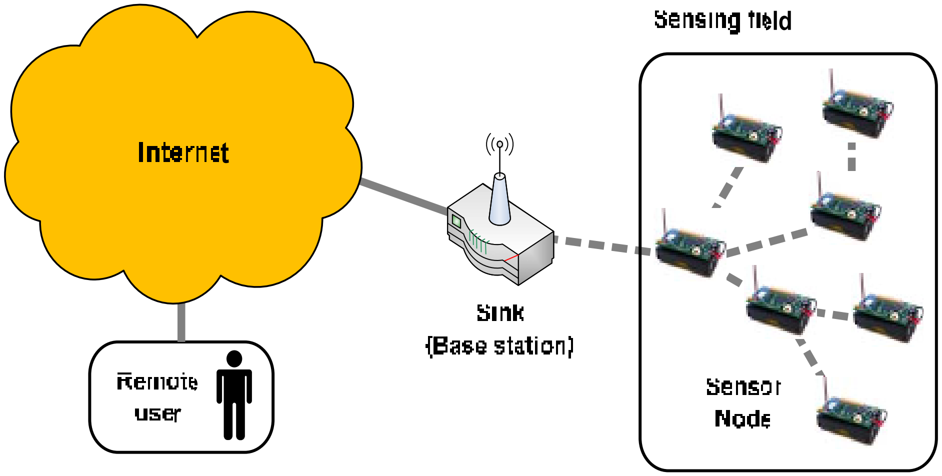
(Sensing / Actuation)

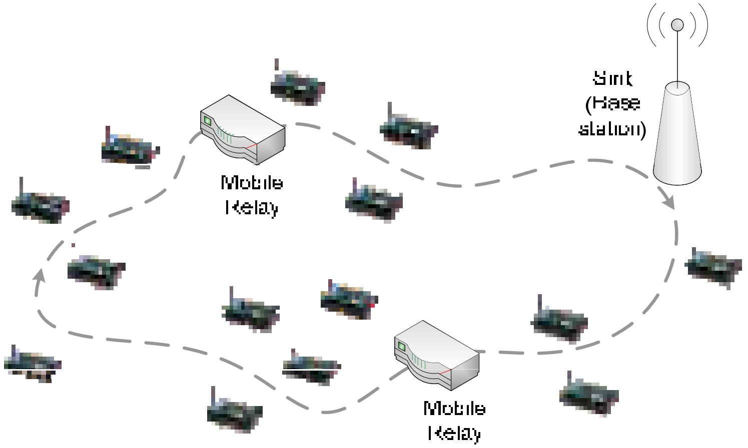
Data Sensing & Collection:

temperature, humidity, pressure, light, velocity, sound, image

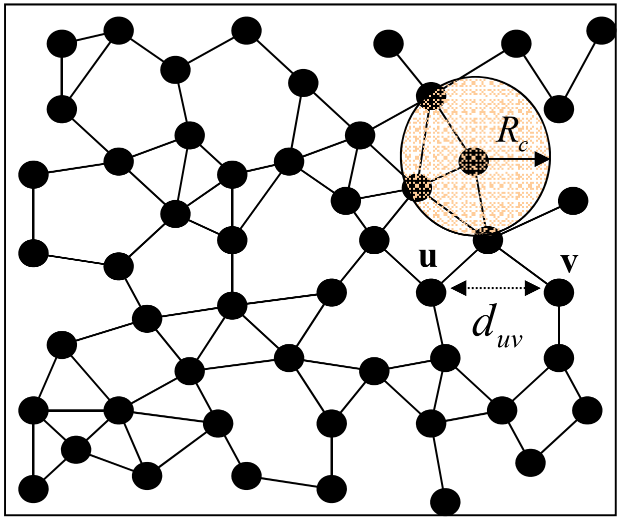
Wireless Sensor Networks (WSN)

Architecture: Static vs. Mobile





Geometric Graph



Communication radius (Rc)

Sensing radius (Rs)

Unit Disk model

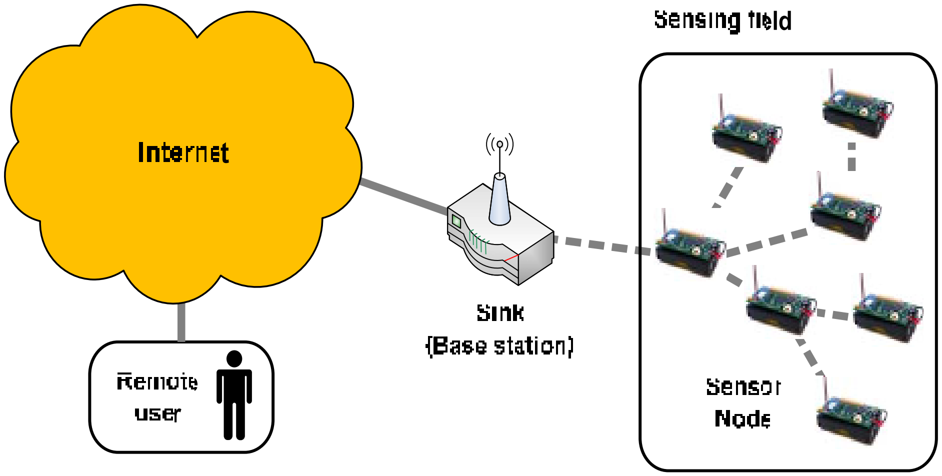
Binary Sensing

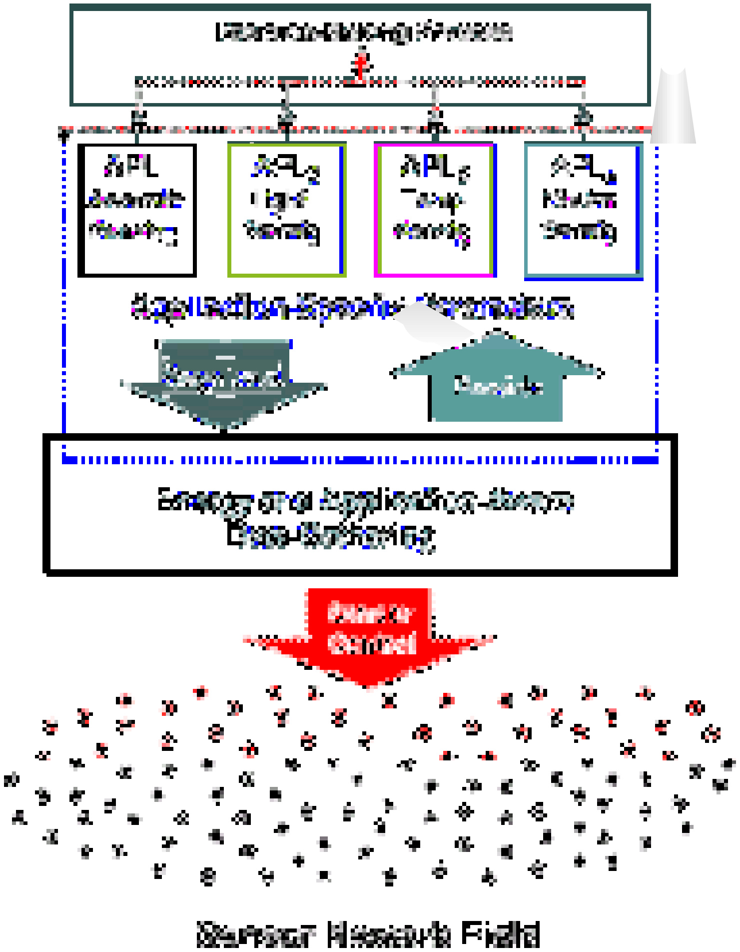
Probabilistic Sensing

M. Di Francesco, S. K. Das, G. Anastasi, “Wireless Sensor Networks with Mobile Elements: A Survey,” *ACM Transactions on Sensor Networks*, Vol. 8, No. 4, Aug. 2011.

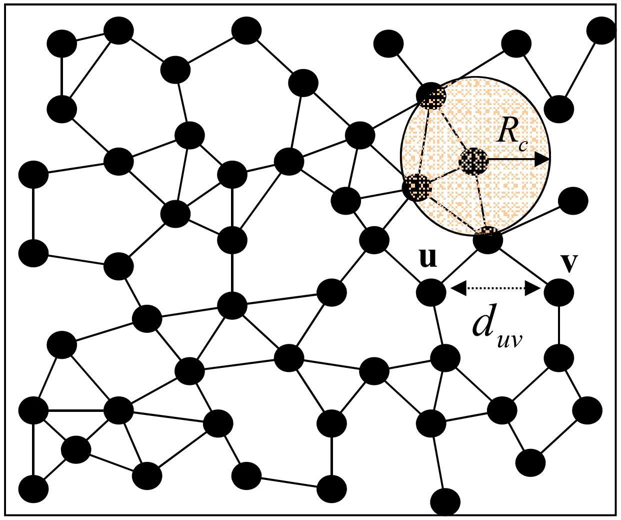
Wireless Sensor Networks (WSN)

Architecture: Static vs. Mobile





Geometric Graph



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Probabilist

M. Di Francesco, S. K. Das, G. Anastasi, "Wireless Sensor Networks with Mobile Elements: A Survey," *ACM Transactions on Sensor Networks*, Vol. 8, No. 4, Aug. 2011.

Emerging Trends in Sensing

- Smartphone as a Sensing Platform
  - Abundance of sensors
  - Multiple wireless technologies
    - WiFi, Bluetooth, long range cellular radio
- Collaborative (Mutimedia) Sensing
  - Scalar sensors: Temperature, humidity, pressure, …
  - Multimedia sensors: Audio, video, image, text, …
- Participatory, Persuasive and Social Sensing
  - Integration of sensing with social networks
  - Incentives for users in sensing campaigns
  - Traffic / accident monitoring, activity, well being, pollution control

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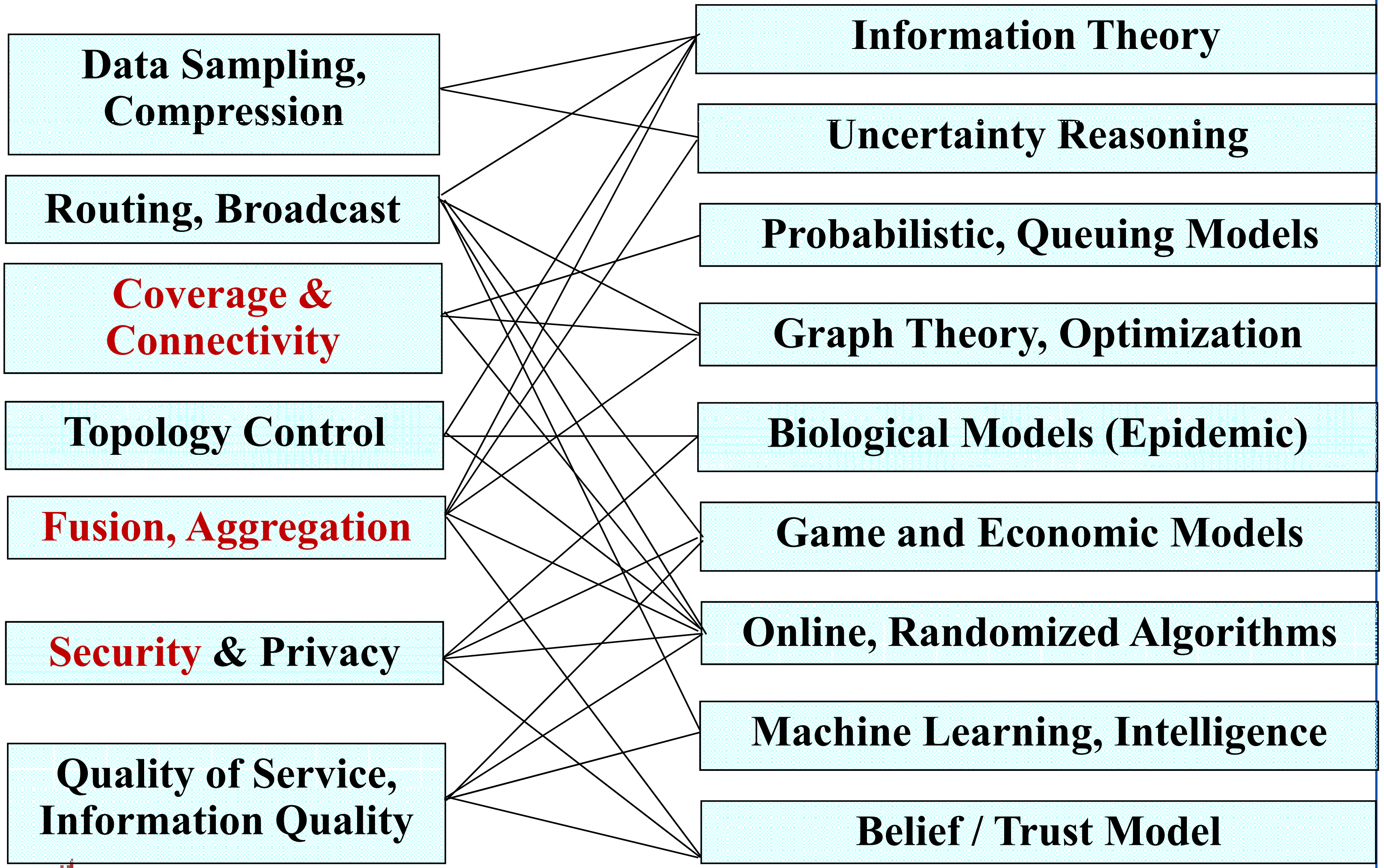
  - Smart Healthcare – Middleware Services
  - Guidelines to Excellent Research
  - Mentoring and Value-Added Education

Lecture 7: Wireless Sensors

- Wireless Sensor Networks (WSNs)
- Fusion in Multimedia WSNs
- Energy-Efficient Algorithms for Fusion
- Graded Coverage and Energy-aware Data Gathering
- Trade-off between Lifetime and QoS (e.g., Latency)
- References

Frameworks and Models



Data Sampling, Compression

Routing, Broadcast

Coverage & Connectivity

Topology Control

Fusion, Aggregation

Security & Privacy

Quality of Service, Information Quality

Information Theory

Uncertainty Reasoning

Probabilistic, Queuing Models

Graph Theory, Optimization

Biological Models (Epidemic)

Game and Economic Models

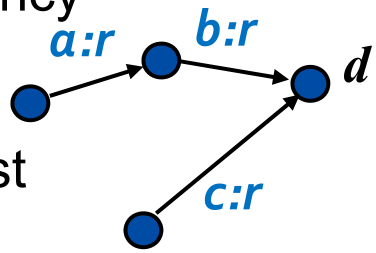
Online, Randomized Algorithms

Machine Learning, Intelligence

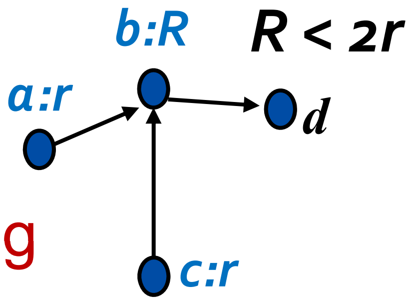
Belief / Trust Model

Fusion in Multimedia WSNs

- What is fusion?
  - Sensory data from proximate nodes has redundancy
    - Exploit spatio-temporal correlation
  - Fusion reduces network load, communication cost
    - less energy consumption, increased lifetime

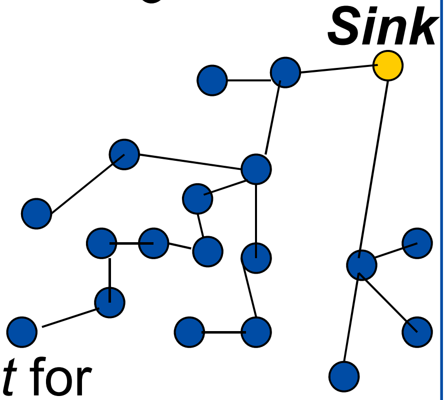


- Fusion is (almost) free for scalar data
  - Average, count, max / min, histogram



- But not free for multimedia (vector) sensing
  - Compression, image fusion, estimation
  - Image fusion: tens of nJ/bit

    (same order of magnitude as communication)



- Fusion-driven routing
  - Construct a fusion tree that minimizes total *cost* for sensor data gathering – fully exploit fusion benefit

Example: Image Fusion

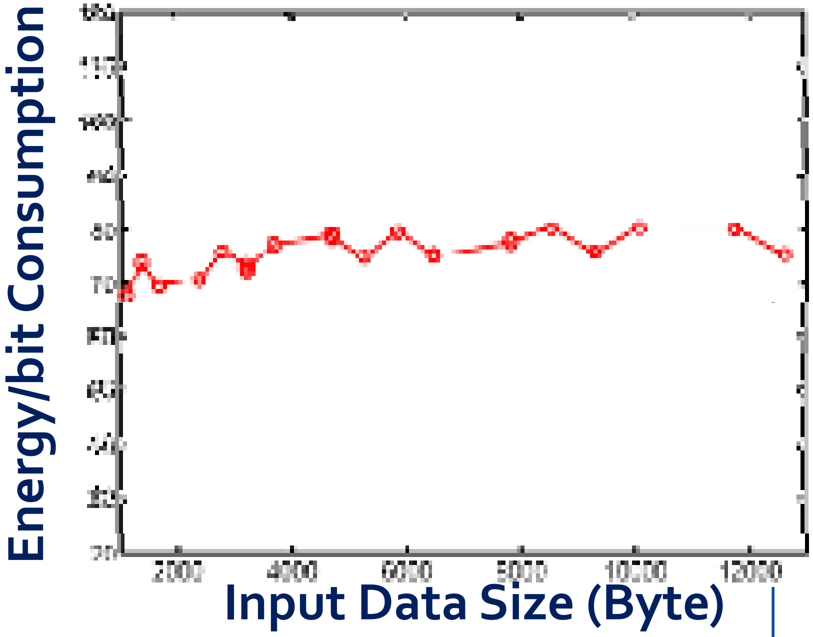
Fusion cost: 70-80 nJ/bit (Motes)

Communication cost: 90-100 nJ/bit

➔ *Same order of magnitude*

Dynamic Decision Control:

Fuse or Not to Fuse?



Y. Liu and S. K. Das, “Information Intensive Wireless Sensor Networks: Potential and Challenges,” *IEEE Communications*, 44(11): 142-147, Nov. 2006.

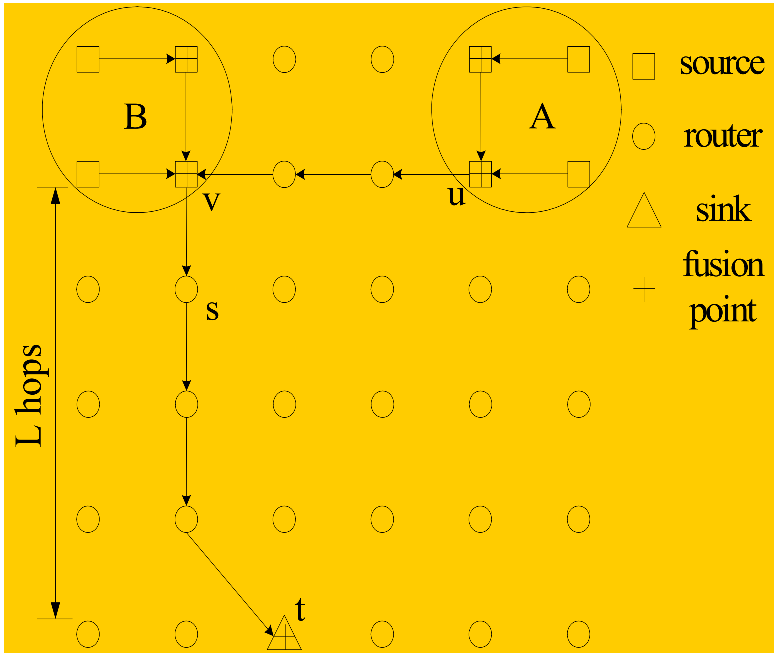
Dynamic Optimization Problem

- Optimize fusion routing tree over both node (fusion) and link (communication) costs: NP-hard
- Routing topology shall determine dynamically
  - Fuse or not to fuse?

    Maximize fusion benefit:

    Trade-off increased fusion cost

    vs. reduced communication cost.
  - How to fuse ?
    - When and where



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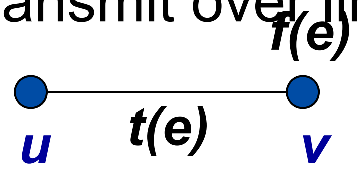
Problem Formulation

- Network model
  - Graph *G = (V, E)*
  - Vertex-set *V = {u, v, … },* Sensor *u* has data sample *w(u)*
  - Edge-set *E = { e = (u, v)* if *u* and *v* are in their radio ranges*},*
  - Link communication cost = *c(e)* per bit
  - Node (or edge) weight *w(u) = w(e)*
- Communication (link) cost for node *u* to transmit over link *e* to nod $t(e) = w(e)c(e)$



- Fusion (node) cost: $f(e) = q(e) \cdot \left(w(u) + \widetilde{w}(v) \right)$

Problem Formulation

- Data Fusion: if *v* is fusion node, correlation coefficient between end nodes *u* and *v* of link *e* is:

$$w(v) = (w(u) + \widetilde{w}(v))(1 - \sigma_{uv})$$

- For each link, introduce a Boolean *x* (0 = no fusion)

$$w(v) = (w(u) + \widetilde{w}(v))(1 - \sigma_{uv} x_{uv}) \quad x_{uv} \in \{0, 1\}$$

Problem Formulation

- Construct a fusion tree that gathers all source data to the sink while minimizing the total cost over all nodes and edges

$$G^* = \operatorname{argmin}_{G'} \sum_{e \in E'_f} \left(f(e) + t(e) \right) + \sum_{e \in E'_n} t(e)$$

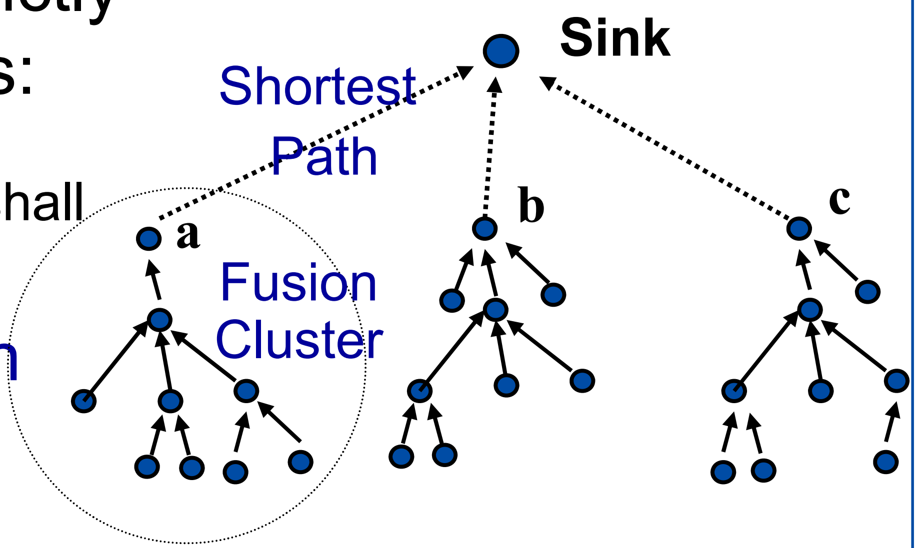
E'_f: edge set where fusion performed; E'_n: fusion not performed

Dynamic Optimization Problem: NP-hard

- Solution: Adaptive Fusion Steiner Tree (AFST)
  - Randomized algorithm
  - Off-line /online, centralized /distributed algorithms

Adaptive Fusion Steiner Tree (AFST)

- The routing tree is distinctly separated into two parts:
  - A lower part where fusion shall always be performed
    - Apply fusion-driven routing algorithm
  - An upper part where fusion shall not be performed at all
    - Use shortest path routing to transmit directly to sink



If fusion is not beneficial at a sensor, it will not be so on succeeding nodes on the path to the sink.

Approximation Ratio = (5/4) log (*k*+1), *k* = cluster size

Baseline: Always Fuse – Minimum Fusion Steiner Tree (MFST)

Experimental Results

- 100 nodes in 50x50 sq. meters
- Communication cost (mJ) is distance dependent
- Unit fusion cost is constant
- Data reduction determined by correlation (physical proximity)
  - Closer the sensors → more data reduction or redundancy
  - Determined by correlation range
- Study the impacts of
  - Transmission Range (Rc)
  - Unit fusion Cost (\omega)
  - Correlation Range (Rs)
- Cost measured as energy

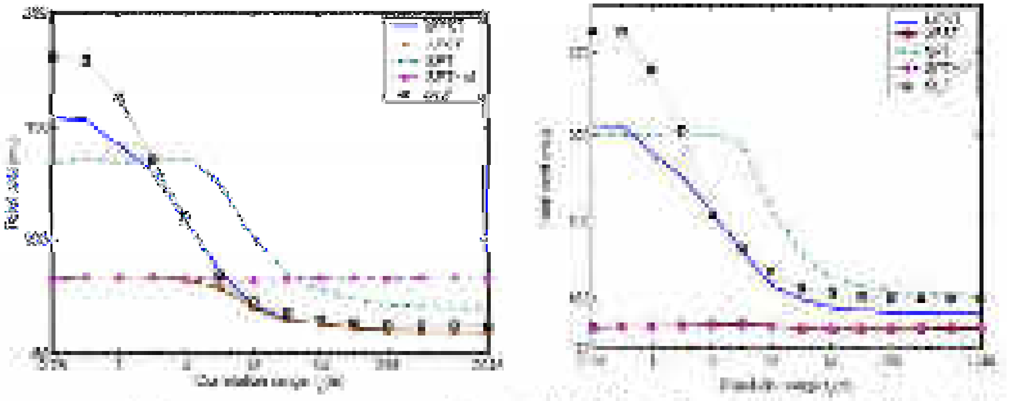
MFST: like AFST but always fusion

MST: Minimum Spanning Tree

SPT: Shortest Path Tree

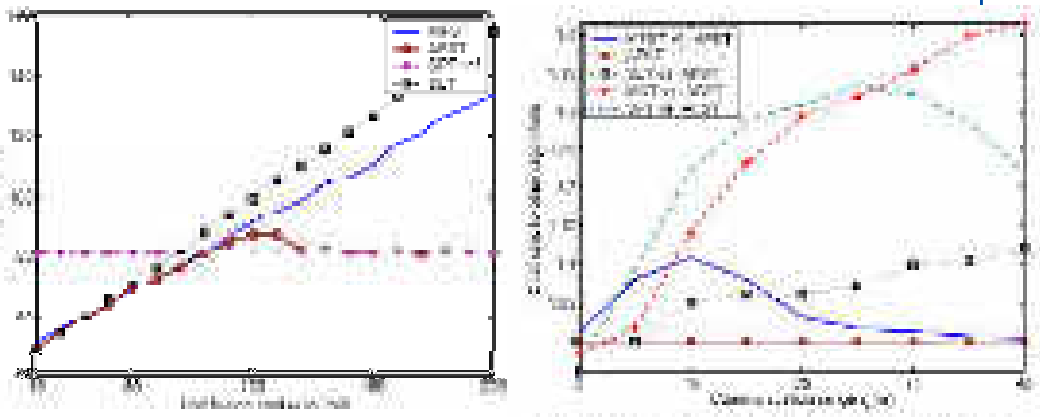
SPT-nf: Shortest Path with no fusion

SLT: Combining MST and SPT



(a) Low fusion cost ($\omega = 50nJ/bit$) (b) High fusion cost ($\omega = 120nJ/bit$)

AFST adapts well with varying correlation (data reduction), communication range (connectivity), and fusion cost



(a) Total cost (b) Cost ratio to other algorithms

Effective Load balancing

Fusion-Driven Routing

- H. Luo, Y. Liu, S. K. Das, “Routing Correlated Data with Fusion Cost in Wireless Sensor Networks”, *IEEE Trans. on Mobile Computing*, 5(11):1620-1632, Nov 2006.
- H. Luo, Y. Liu, S. K. Das, “Adaptive Data Fusion for Energy Efficient Routing in Wireless Sensor Networks”, *IEEE Trans. on Computers*, 55(10): 1286-1299, 2006.
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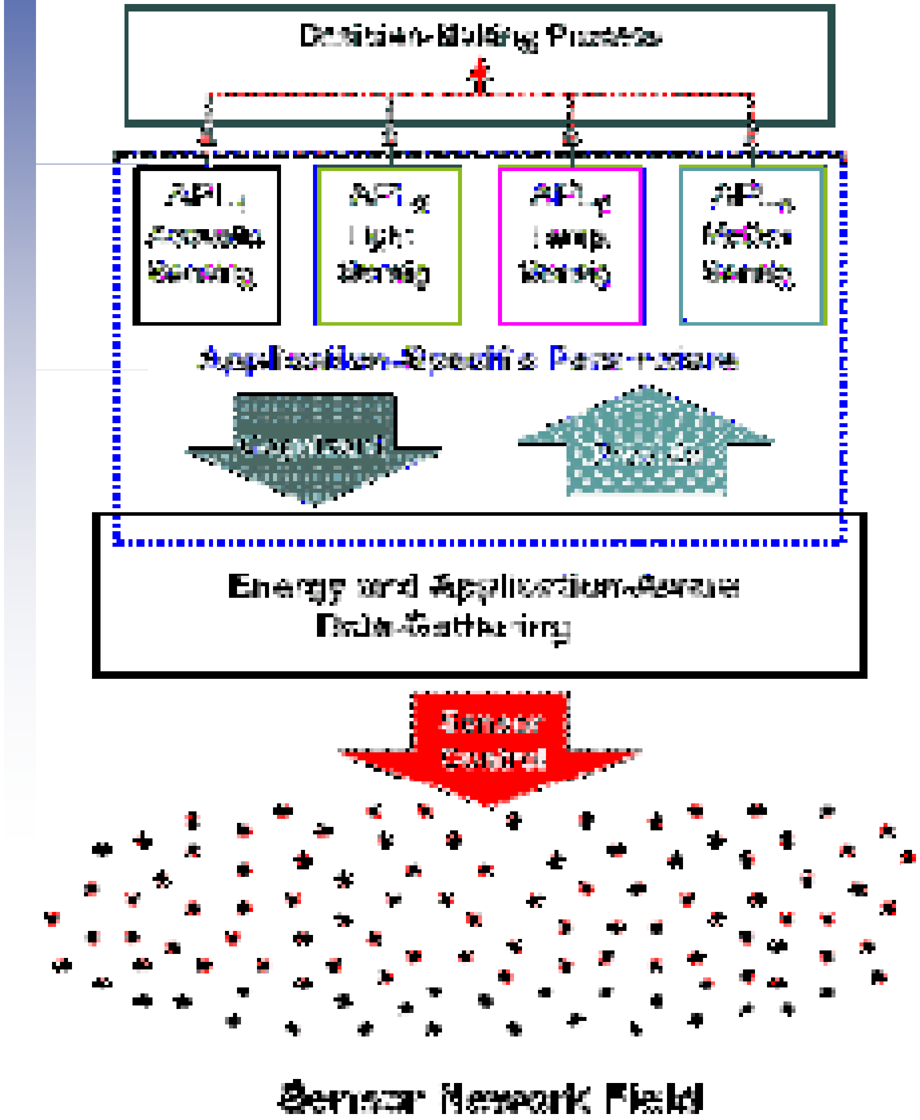
Energy- and Coverage-Aware Data Gathering



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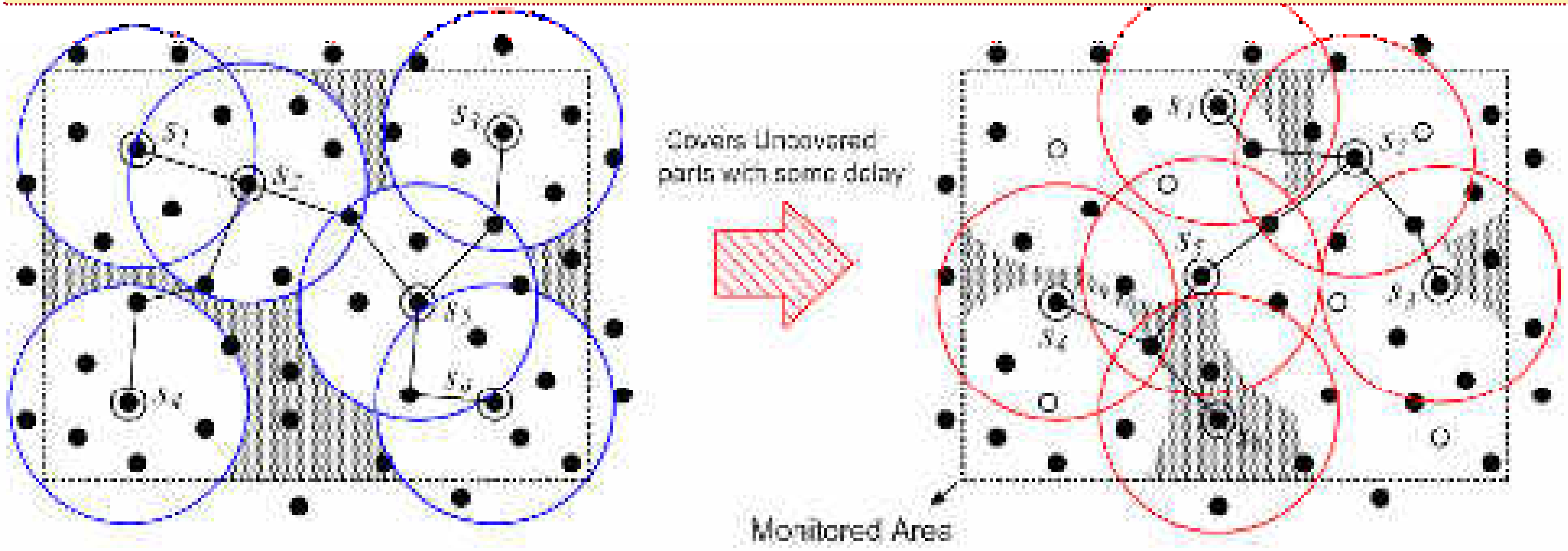
Energy- and Coverage-Aware Data Gathering

- Extend Network Lifetime: Reduce energy consumption by adjusting sensor's duty cycle (sleep-wakeup) when they collect and report data.
- Probabilistic Coverage: Select *minimum k* of sensors to meet *desired sensing coverage* (DSC), ψ, in each round, for graded coverage (say, 90%)
- Trade-off: *Sensing coverage* (energy consumption and data accuracy) vs. *data reporting latency* (QoS).
- *How to select k disjoint subsets of connected sensors in each round such that the monitored area is entirely covered in \delta rounds?*



Selecting Minimum *k* Sensors

- Probability that point *(x,y)* ∈ Q not covered by a random sensor:

$$P_Q(x,y) = \int_{D-A(x,y)}\int f(x,y)\,dx\,dy = \frac{D - A(x,y)}{D}, \quad \text{where} \quad f(x,y) = \frac{1}{D}$$

- Mean area of Q not covered by uniformly selected *k* sensors:

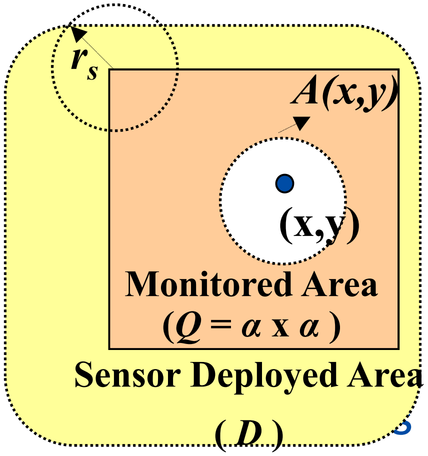
$$E[\eta] = \int_Q\int (P_Q(x,y))^k\,dx\,dy$$

$(P_Q(x,y))^k$ = probability that *(x,y)* ∈ Q not covered by *k*-selected sensors

- Probability that a point covered by at least one of *k*-sensors:

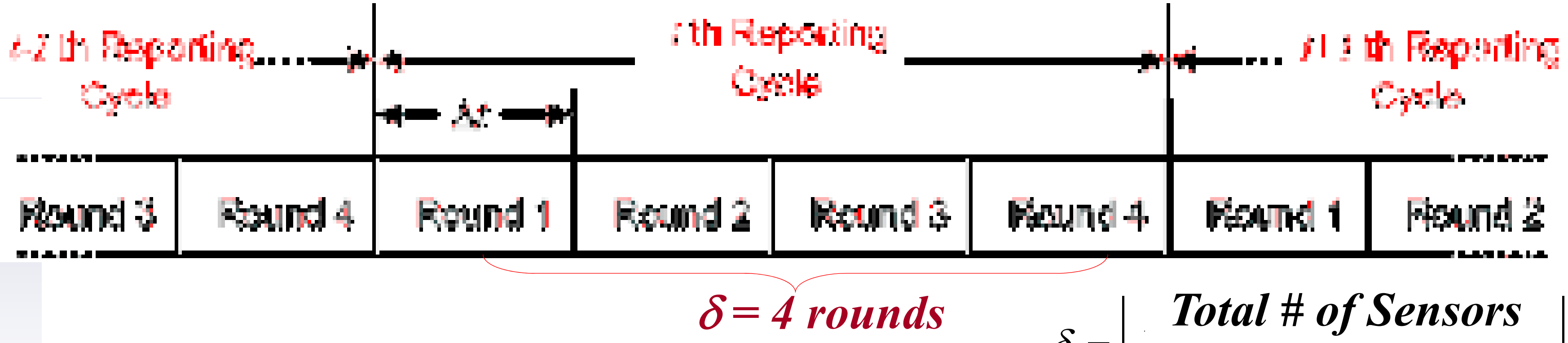
$$\psi = 1 - \frac{E[\eta]}{\alpha^2} = 1 - \left(\frac{\alpha^2 + 4\alpha r_s}{\alpha^2 + 4\alpha r_s + \pi r_s^2}\right)^k$$

$$k = \left\lceil \frac{\log(1-\psi)}{\log\left(\frac{\alpha^2 - 4\alpha r_s}{\alpha^2 + 4\alpha r_s + \pi r_s^2}\right)} \right\rceil$$



Coverage-Adaptive Sensor Selection

- Coverage-Adaptive: *k* decided by specified DSC (desired sensing coverage)
- Data Reporting Round and Cycle



$$\delta = \left\lfloor \frac{Total\ \#\ of\ Sensors}{k} \right\rfloor$$

- **Non-disjoint Randomized Selection (*NRS*)**

  - Sensors elect themselves as one of *k* sensors in each reporting round based on probability $\frac{k}{|V|}$, where V is the set of all sensors
  - Data reporting latency to cover entire monitored area not fixed

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Disjoint *k*-Sensor Selection

W. Choi and S. K. Das, “A Novel Framework for Energy-conserving Data Gathering in Sensor Networks”, *IEEE INFOCOM*; *ACM TOSN 2012.*

Non-Fixed Disjoint Randomized Selection (N-DRS)

- All sensors report their sensed data exactly once during $\delta = \left\lfloor \frac{|V|}{k} \right\rfloor$ rounds (a cycle)

- Sensors randomly choose one of δ rounds as their data reporting in every cycle and maintain a reporting bit sequence (RS)

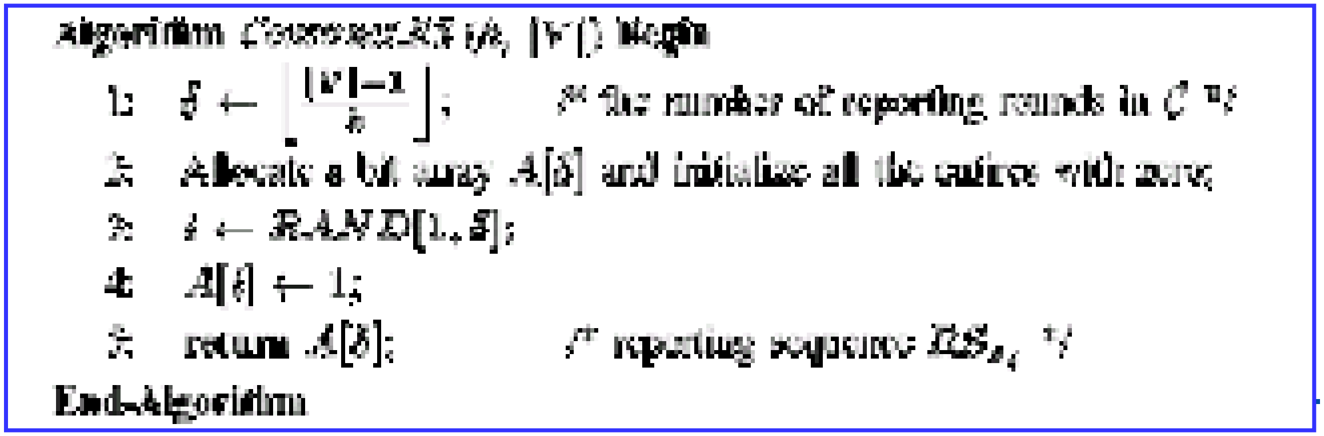
Example: δ = 4 and if the random draw is 1st round, then RS = “1000”

- Entire monitored area is covered within a fixed delay

Fixed Disjoint Randomized Selection (F-DRS)

- Similar to N-DRS but it chooses data reporting round only once

- Entire monitored area is covered within a fixed delay

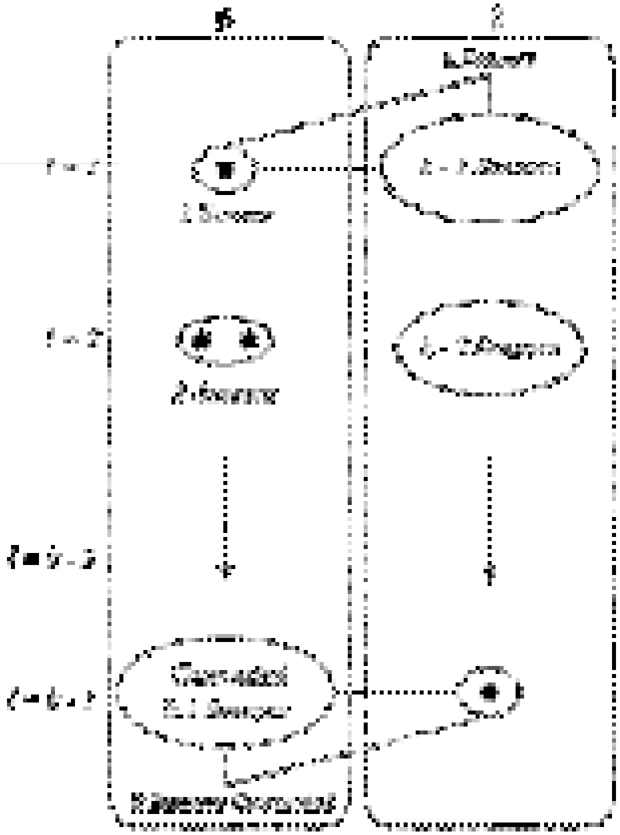


```
Algorithm Construct_RS (k, |V|) Begin
    $\delta \leftarrow \left\lfloor \frac{|V|-1}{k} \right\rfloor$;        /* the number of reporting rounds in $C$ */
    Allocate a bit array $A[\delta]$ and initialize all the entries with zero;
    $i \leftarrow RAND[1, \delta]$;
    $A[i] \leftarrow 1$;
    return $A[\delta]$;        /* reporting sequence $RS_{s_i}$ */
End-Algorithm
```

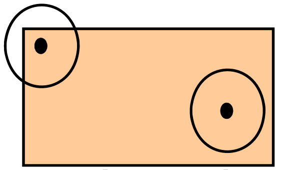
Connectivity of Selected Sensors

Probabilistic Model: Connectivity in Random Geometric Graph

- Measure average overlapped area of radio range in sensor deployed area.
- Probability that a sensor has at least one neighbor within radio range is



$$P_i^s = \frac{\textbf{Average Overlapped Area}}{\textbf{Sensor Deployed Area}}$$



Sensor deployed area

$$Pr_{\beta}^{1} = \sum_{j=1}^{k-1} \binom{k-1}{j} (P_{ss})^{j} (1-P_{ss})^{k-1-j}$$

$$Pr_{\beta}^{2} = Pr_{\beta}^{1} \times \left(1-\left(1-\sum_{j=1}^{k-2} \binom{k-2}{j} (P_{ss})^{j} (1-P_{ss})^{k-2-j}\right)^{2}\right)$$

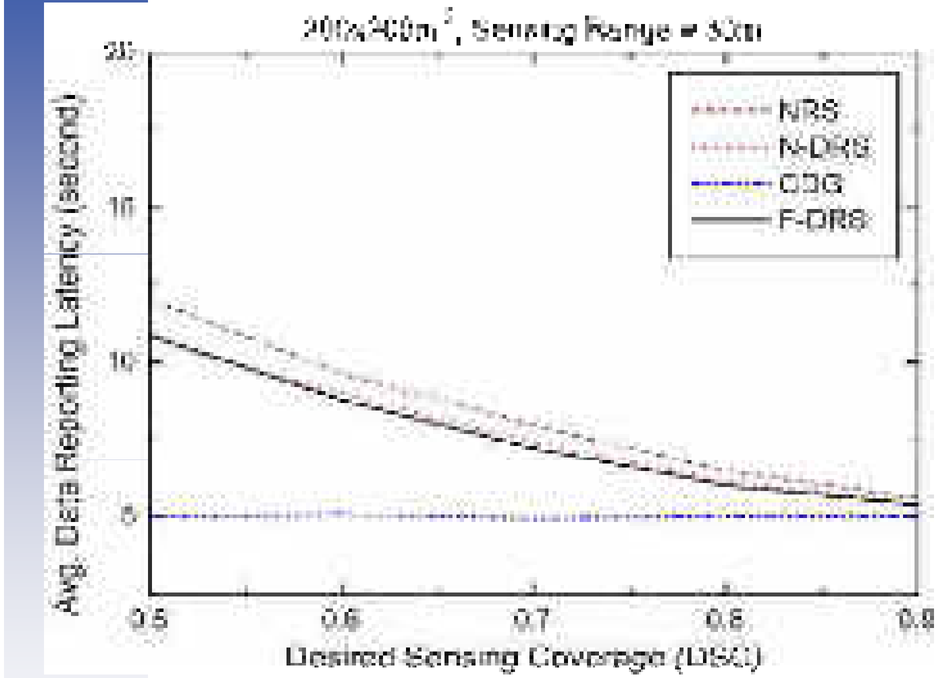
$$\vdots \qquad \vdots$$

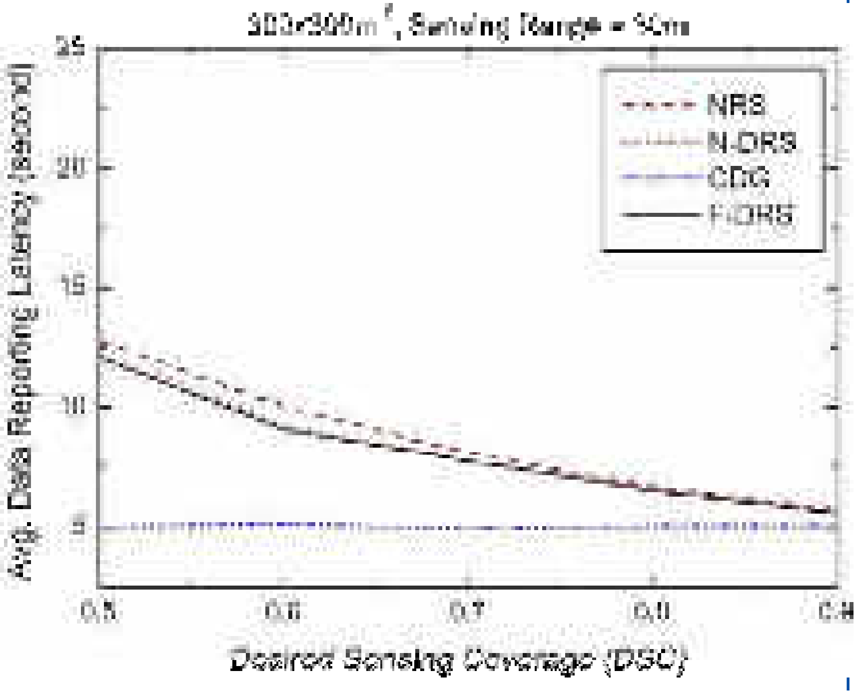
$$Pr_{\beta}^{k-2} = Pr_{\beta}^{k-3} \times \left(1-\left(1-\sum_{j=1}^{2} \binom{2}{j} (P_{ss})^{j} (1-P_{ss})^{2-j}\right)^{k-2}\right)$$

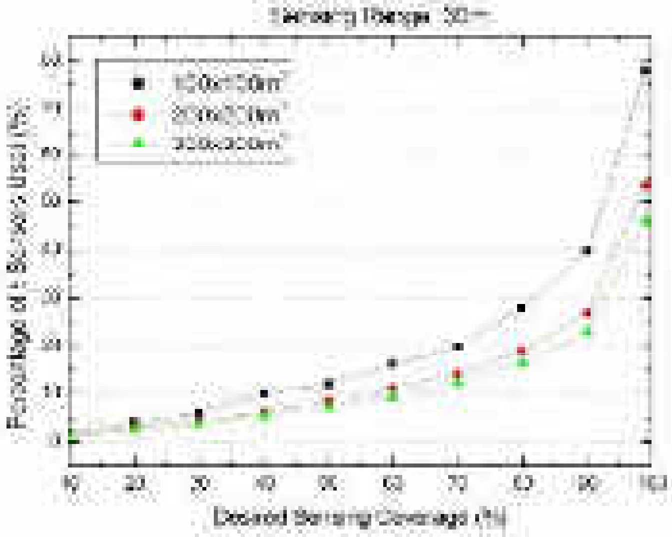
$$Pr_{\beta}^{k-1} = Pr_{\beta}^{k-2} \times (1-(1-P_{ss})^{k-1})$$

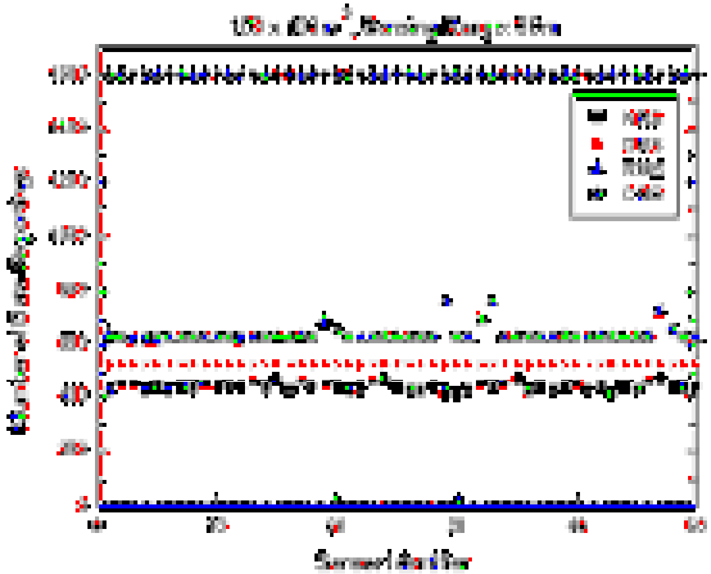
Use Chernoff's bound to prove that the selected subset of sensors are almost always connected with very high probability (asymptotically 1).

Data Reporting Latency

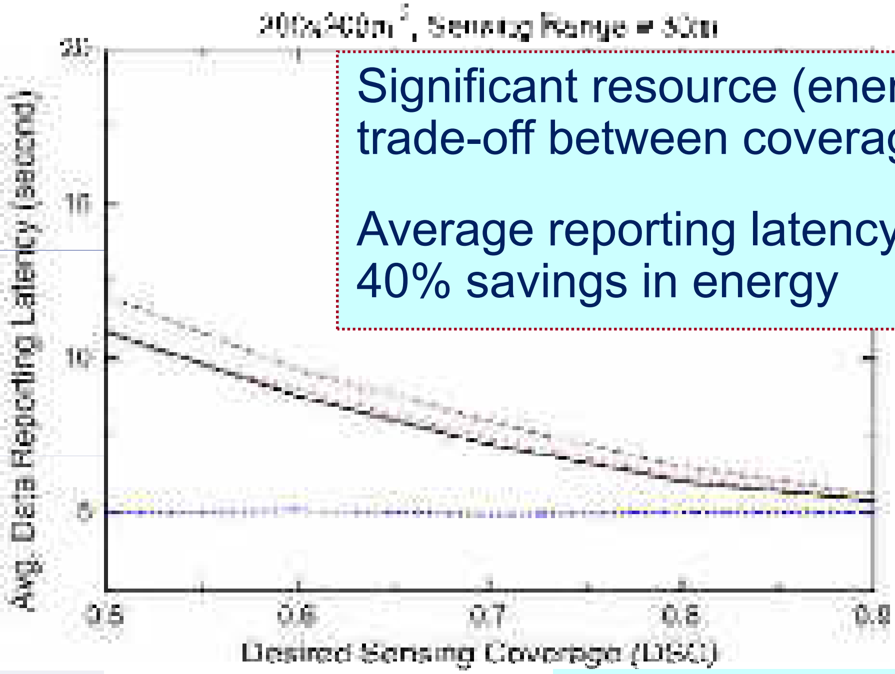


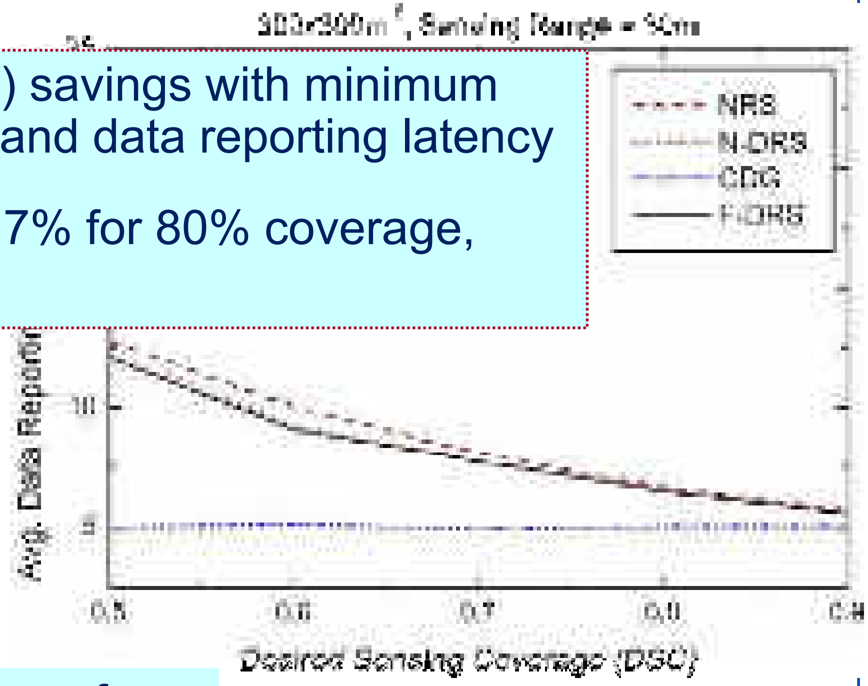






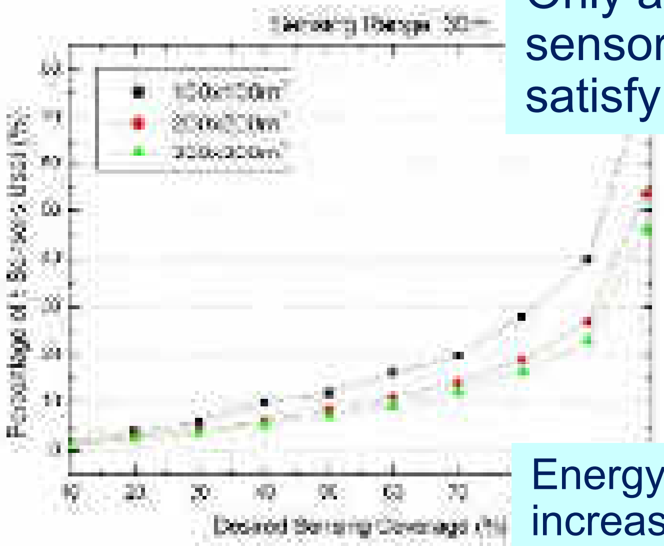
Data Reporting Latency



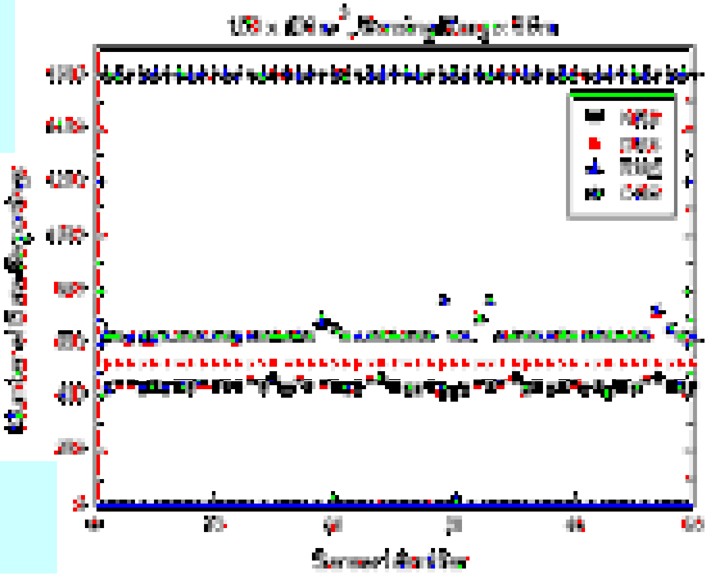


Significant resource (energy) savings with minimum trade-off between coverage and data reporting latency

Average reporting latency < 7% for 80% coverage, 40% savings in energy



Only a small fraction of sensors are duty cycled to satisfy coverage and QoS



Energy conservation rate increases w/ graded coverage

Energy-Efficient Coverage

- G. Ghidini and S. K. Das, “Energy-efficient Markov Chain-based Duty Cycling Schemes for Greener Wireless Sensor Networks,” *ACM Journal of Emerging Technologies in Computing Systems*, 8(4), Dec 2012.
- W. Choi, G. Ghidini, and S. K. Das, “A Novel Framework for Energy-Efficient Data Gathering with Random Coverage in Wireless Sensor Networks,” *ACM Transactions on Sensor Networks*, 8(4), Sept 2012.
- M. Di Francesco, G. Anastasi, M. Conti, S. K. Das, “Reliability and Energy-efficiency in IEEE 802.15.4/ZigBee Sensor Networks: An Adaptive and Cross-layer Approach,” *IEEE Journal on Selected Areas of Communications*, 29(8): 1508-1524, Aug 2011.
- G. Ghidini and S. K. Das, “An Energy-Efficient Markov Chain-based Randomized Duty Cycling Scheme for Wireless Sensor Networks,” *Proc. IEEE ICDCS*, pp. 67-76, 2011.
- H. Ammari and S. K. Das, “A Study of *k*-Coverage and Measures of Connectivity in 3D Wireless Sensor Networks,” *IEEE Trans on Computers*, 59(2): 243-257, Feb 2010.
- W. Choi and S. K. Das, “CROSS: Probabilistic Constrained Random Sensor Selection in Wireless Sensor Networks,” *Performance Evaluation*, 66(12): 754-772, 2009.
- H. M. Ammari and S. K. Das, “Critical Density for Coverage and Connectivity in Three-Dimensional Wireless Sensor Networks Using Continuum Percolation,” *IEEE Transactions on Parallel and Distributed Systems*, 20(6): 872-885, June 2009.
- W. Choi and S. K. Das, “A Novel Framework for Energy-Conserving Data Gathering in Wireless Sensor Networks,” *IEEE INFOCOM* 2005.

Ongoing Projects

- Paradigm shift – Asynchronous sampling, architectures, protocols and optimization in multimedia WSNs
  - Ultra-energy efficient, Scalable, Reliable, Secured
  - J. Wang, Y. Liu, and S. K. Das, “Energy Efficient Data Gathering in Wireless Sensor Networks with Asynchronous Sampling," ACM Transactions on Sensor Networks, Vol. 6, No. 3, 2010. (Preliminary version in IEEE INFOCOM 2008)
  - H. Luo, H. Tao, H. Ma, and S. K. Das, “Data Fusion with Desired Reliability in Wireless Sensor Networks,” *IEEE Transactions on Parallel and Distributed Systems,* Vo. 22, No. 3, pp. 501-513, March 2011.
- Reprogramming or debugging (mobile) sensor networks
  - Large scale, high density deployment, often inaccessible
  - P. De, Y. Liu and S. K. Das, “Energy Efficient Reprogramming of a Swarm of Mobile Sensors,” IEEE Transactions on Mobile Computing, Vol. 9, No. 5, 2010. (Preliminary version in IEEE PerCom 2008)

Ongoing Projects

- Information and Context Quality for big data applications (e.g., smart environments, health care, security)
- Tradeoff - Energy vs. Context Quality: Multi-context recognition under ambiguous contexts and ontology

- H. J. Choe, P. Ghosh and S. K. Das, “QoS-aware Data Reporting in Wireless Sensor Networks,” *Proc. 1st IEEE Workshop on Information Quality and QoS in Pervasive Computing* (IQ2S), Mar 2009.

- N. Roy, G. Tao and S. K. Das, “Supporting Pervasive Computing Applications with Active Context Fusion and Semantic Context Delivery,” Pervasive and Mobile Computing, Vol. 6, No. 1, pp. 21-42, Feb 2010.

- N. Roy, C. Julien, and S. K. Das, “Resource-Optimized Quality-Assured Ambiguous Context Mediation in Pervasive Environments,” 6th Int’l Conf on Heterogeneous Networking for Quality, Reliability, Security and Robustness (QShine'09), Spain, pp. 232-248, Nov 2009. (Best Paper Award). IEEE Trans on Mobile Computing, Vol. 11, No. 2, pp. 218-229, 2012.

- N. Roy, A. Misra, C. Julien , S. K. Das, “Energy-Efficient Quality Adaptive Framework for Multi-Modal Sensor Context Recognition,” *IEEE Conf on Pervasive Computing and Communications*, Mar 2011. (Best Paper Candidate). Extended version in ACM Transactions on Sensor Networks, 2013.

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Lecture 8: Pervasive Computing

- ☐ Enabling Technologies
- ☐ Pervasive Computing
- ☐ Cyber-Physical Social Convergence
- ☐ CPS Applications
- ☐ Internet of Things
- ☐ Uncertainty Challenges

Enabling Technologies

- **Smart Devices**
  - – Embedded systems, MEMS, Sensors
  - – Portables, Mobile and Wearable Computers
  - – RFID, Blue tooth, PDAs, iPods, iPhones, …
- **Wireless Mobile Networking**
  - – Personal and Body Area Networks (PAN, BAN)
  - – WLAN, Ad hoc and Sensor Networks
  - – Wide Area Cellular Networks (GPRS, CDMA, UMTS, IMS, 3G/4G)
  - – Wireless Mesh, Wireless Internet
- **Computing Technologies**
  - – Distributed, Grid, Peer-to-Peer, and Embedded Computing
  - – Mobile, Pervasive / Ubiquitous, Wearable, and Autonomic Computing
- **Mobile / Pervasive Systems and Services**
  - – Middleware, Agents
  - – HCI (multi-modal – voice, touch, GUI, brain-wave, implied command, …)

Enabling Technologies

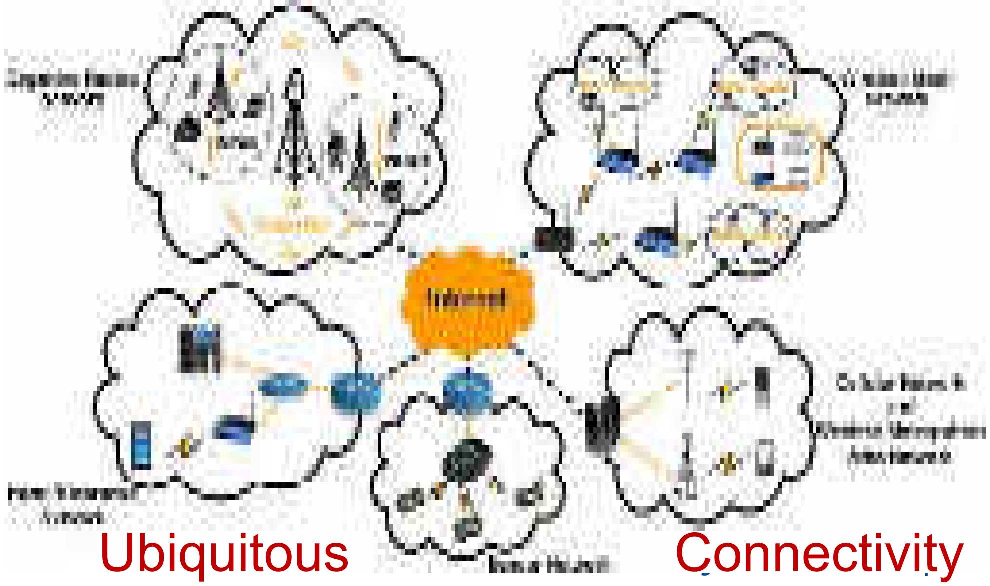
Middleware Services

- Data / storage / computation / service
- Agent based technologies, J2ME
- Intelligent Decision Making
- HCI, MMI, M2M (voice, touch, GUI)

Computing Paradigms

- Distributed, Grid, P2P, Cloud Computing
- Mobile, Pervasive / Ubiquitous Computing

Smart Multi-modal Devices



Ubiquitous Connectivity

Premise

Smart Multi-modal Devices, Heterogeneous Wireless Networks, Computing paradigms, Middleware Services

- Ultra light, energy-efficient, embedded devices
- Sensors are pervasive: coffee mugs to clothing to buildings
- Wireless and ubiquitous connectivity taken for granted
- Opportunistic networking embedded in pervasive computing
- Cognitive networks, overlaying architectures and protocols
- Content rich wireless, sensor and social media applications
- Information deluge: mechanisms to record every event in life

→ **New paradigms for information management**

Pervasive Computing

"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."

Mark Weiser

"The Computer for the 21st Century"

Scientific American, Sept 1991

Why Pervasive Computing?

- Societal Grand Challenges
  - Pervasive Security

    Security and safety of people and infrastructures
  - Smart Healthcare

    Activities of Daily Living, wellness management, m-Health
  - Energy & Sustainability

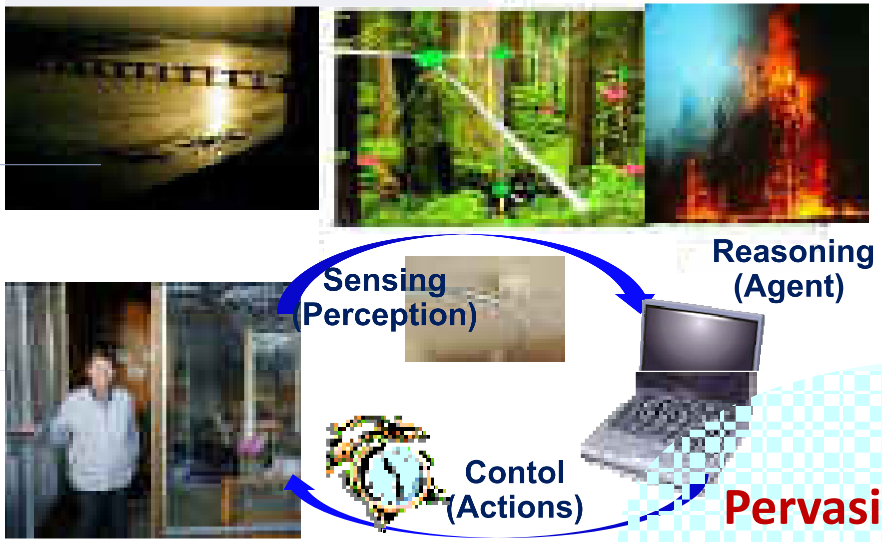
    Smart energy management, carbon footprint, natural resources
  - Extreme Events Management

    Natural and inflicted disasters, emergency response

D. J. Cook and S. K. Das, "Pervasive Computing at Scale: Transforming the State of the Art," *Pervasive and Mobile Computing*, 8(1): 22-35, Feb. 2012.

Sensing, Reasoning and Control

Environment Sensing



Emergency Response

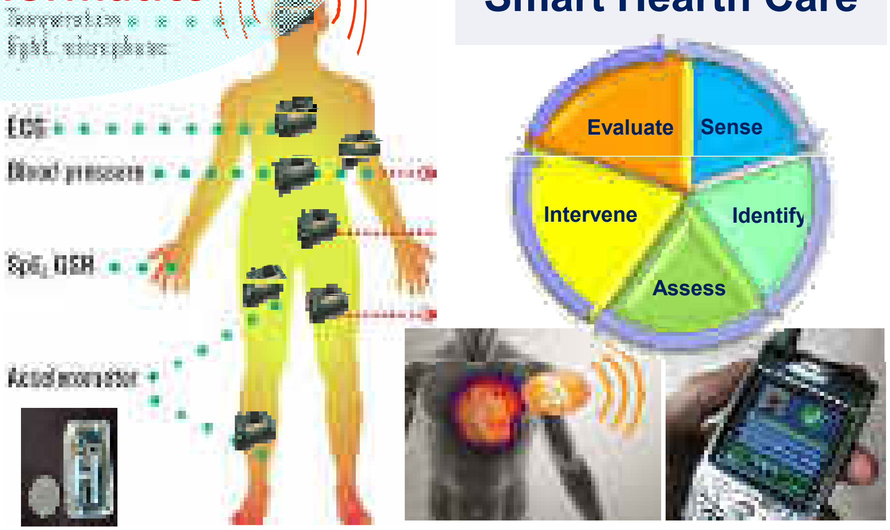
Situation-Awareness: Humans as sensors feed multi-modal data streams

Pervasive Computing

Social Informatics

People-Centric Sensing

Smart Hearth Care



Cyber-Physical-Social Convergence

CPS are natural or engineered systems that integrate sensing, communication, computing and control: WSN is ideal technology

M. Conti, S. K. Das, et al. "Looking Ahead in Pervasive Computing: Challenges and Opportunities in the Era of Cyber-physical Convergence. *Pervasive and Mobile Computing, 8*(1): 2-21, 2012.

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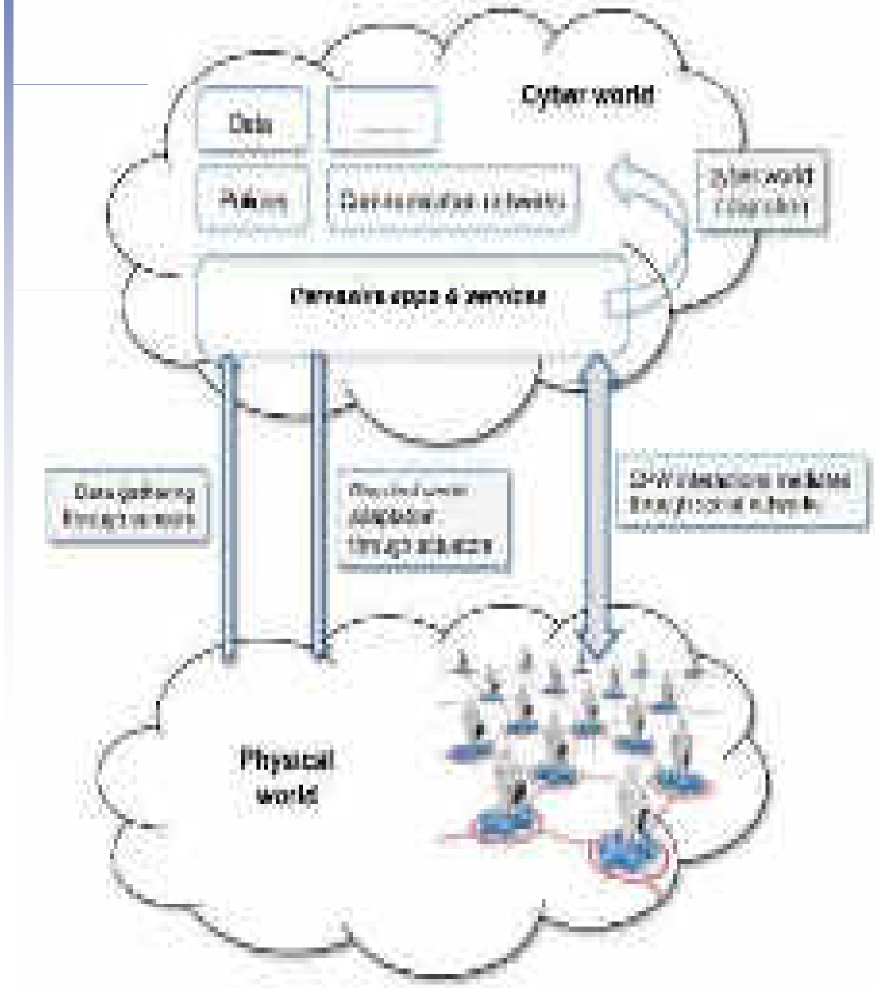
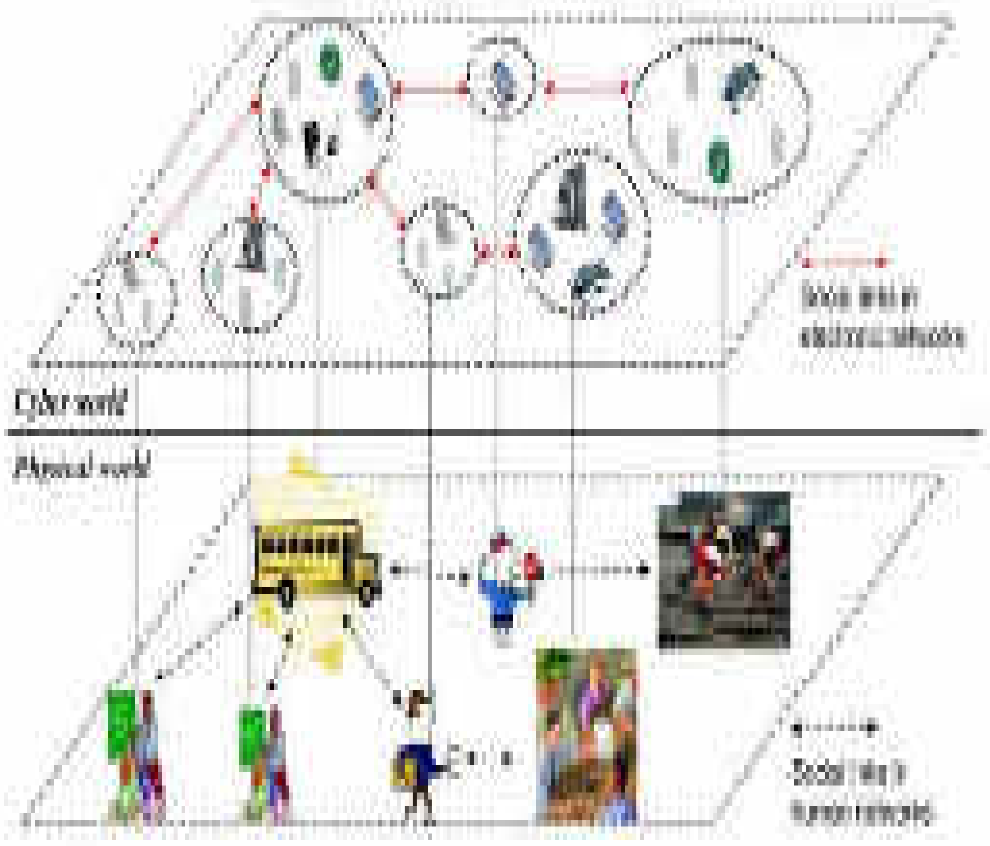




M. Conti, S. K. Das, et al. “Looking Ahead in Pervasive Computing: Challenges and Opportunities in the Era of Cyber-physical Convergence. *Pervasive and Mobile Computing, 8*(1): 2-21, 2012.

CPS Applications

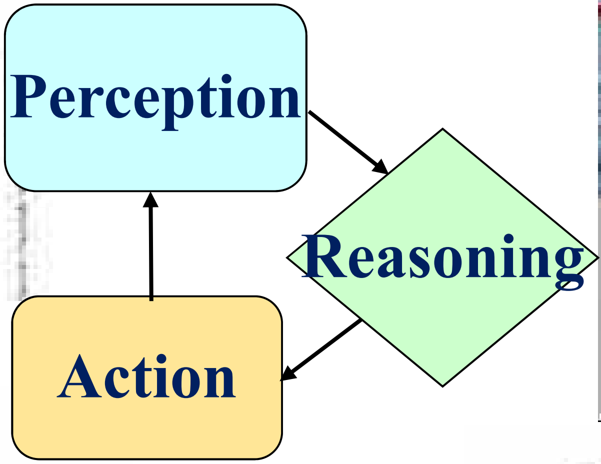
Intelligent Transportation	▪ Fast, energy-efficient aircrafts ▪ Automated highway, aerial nets ▪ Safer, efficient automobiles	
Energy, Sustainability, Automation	▪ Green, Zero carbon building ▪ Smart homes, offices, hospitals ▪ Smart grid, microgrid generator	
Smart Healthcare	▪ Effective in-home health care ▪ Capable devices for diagnosis ▪ Internal & external prosthetics	
Critical Infrastructure Protection	▪ Reliability, safety, security ▪ Buildings, airports, harbors, bridges, utility plants	

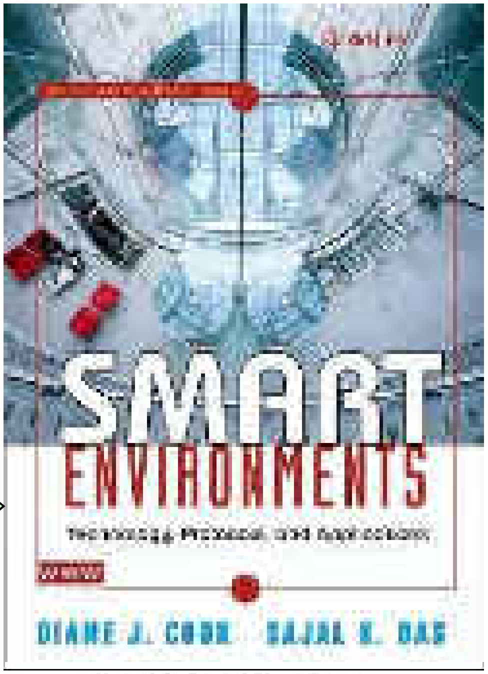
Pervasive sensing, networking, computing, and control

→ Cyber-Physical Systems (CPS) → Internet of Things (IoT)

How is IoT Different?

Ambient Intelligence?



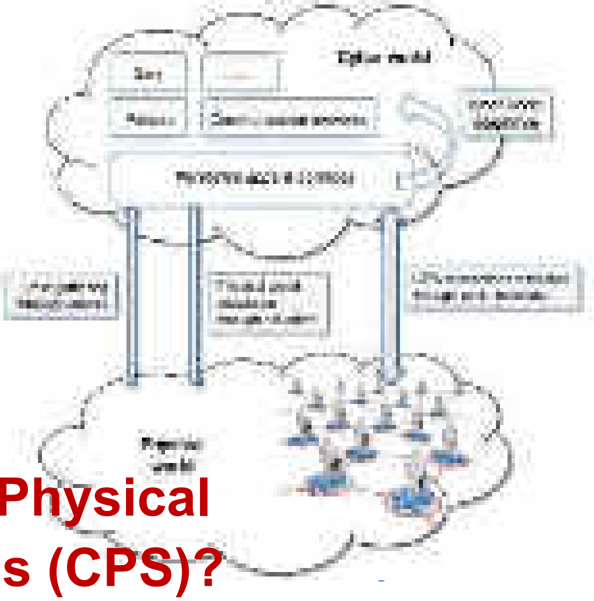


SMART ENVIRONMENTS

Technology, Protocols, and Applications

DIANE J. COOK SAJAL K. DAS

Pervasive Computing?



Cyber-Physical Systems (CPS)?

Uncertainty Challenges

- How to deal with inherent uncertainty in sensor networks?

⇨Sensing, wireless communications, mobility, topology control, coverage, routing, resources (CPU, memory, bandwidth, energy)

⇨Distributed collaboration and coordination, data gathering, aggregation (fusion), processing, decision making, duty cycling, …

- How to determine context and situation awareness?

How to unambiguously capture context / situation despite uncertain (noisy) and incomplete information? What is the semantic model?

- How to provide higher information assurance?

➢ Accuracy, reliability, fault-tolerance, resiliency, security, privacy, trust?

➢ How to protect against adversarial, malicious or replication attacks?

- How to manage big data?

How to handle big data and higher data rates from multi-modal sensors and social networks under resource constraints?

Dealing with Uncertainty in CPS

- Sources of uncertainty in natural and engineered systems
  - Environmental uncertainties, e.g., external noise
  - Noisy and disturbed measurements or observations
  - Stochastic topological variations
  - Incomplete information about system state

  - How does uncertainty impact on CPS performance?

  - How to characterize local dynamics and estimate performance?

  - How to make CPS more dependable and secure?

  - What are the guiding principles for reliable design, operations and management of CPS?

Uncertainty Measures

- Shanon's Entropy: $H(X) = -\sum_{x \in \mathcal{X}} p(x) \lg p(x)$
- Joint entropy: $H\left(X, Y\right) = -\sum_{x \in \mathcal{X}} \sum_{y \in \mathcal{Y}} p(x, y) \lg\ p(x, y)$
- Entropy Rate: for a stationary process or sequence $V = \{V_i\}$
  - Per symbol entropy: $H\left(\mathcal{V}\right) = \lim_{n \to \infty} \frac{1}{n} H\left(V_1, V_2, \ldots, V_n\right)$
  - Conditional entropy given the past history:

$$H'\left(\mathcal{V}\right) = \lim_{n \to \infty} H\left(V_n \mid V_{n-1} V_{n-2} \cdots V_1\right)$$

- Universal Model: for a stationary process $V = \{V_i\}$
  - $H'(V_n \mid V_{n-1}, V_{n-2}, \ldots, V_1)$ decreases with increasing *n*
  - In the limit : $H'(V) = H(V)$

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Lecture 9: WSN Security

- ❑ Pervasively Secure Infrastructure
- ❑ Security Challenges and Issues
- ❑ Multi-Level Security Framework
- ❑ CPS Security
- ❑ References

Pervasively Secure Infrastructures (PSI): Integrating Smart Sensing, Data Mining, Pervasive Networking and Community Computing

http://crewman.uta.edu/psi

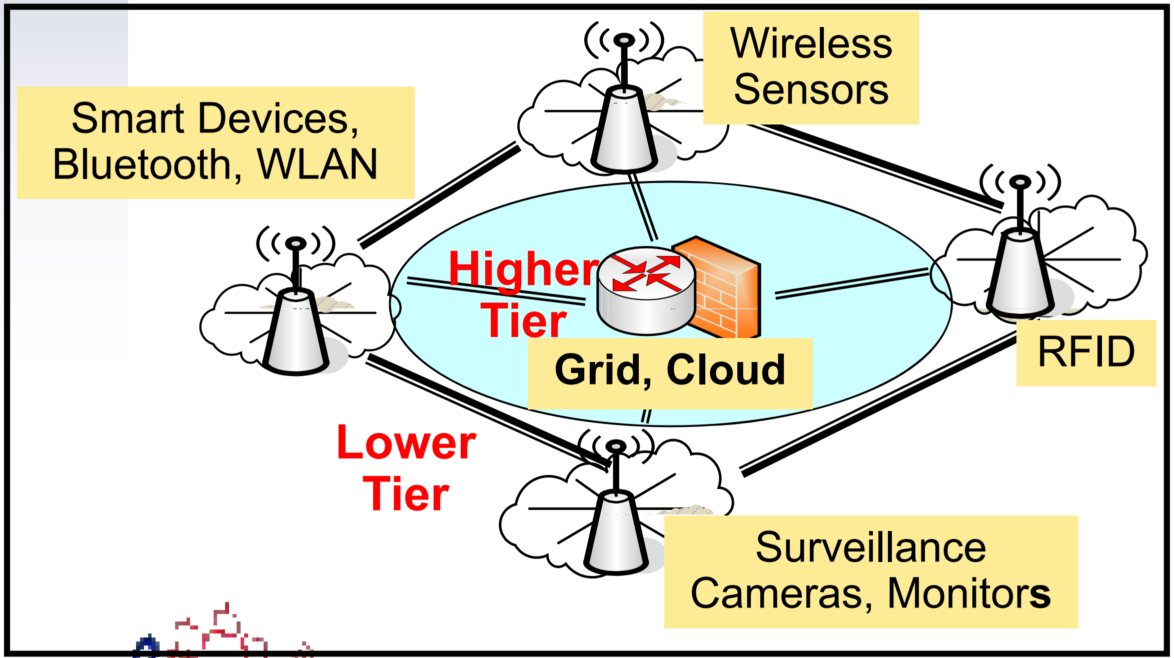
NSF Project (2004-2013)

Sajal K. Das

PSI Overview

Goal: Create a technology-enabled, multi-level security framework for monitoring, preventing, or recovering from natural and inflicted disasters.

Technology: Embedded sensors, RFID, wireless networking, pervasive computing, agent technologies, middleware.



Broader Impact:

Infrastructure and border security, surveillance

- Transportation (air, rail)
- Utility plants (water, gas, electricity, nuclear)
- Public / private places (airport, train stations, shopping malls, parks)

Methodology:

Information theory, uncertainty reasoning, epidemic theory, trust model, game theory, graph theory, data mining

Sajal K. Das

Research Goals & Challenges

- How to efficiently collect context / situation-aware data from multi-modal heterogeneous sensors, surveillance, and tracking devices?
- How to correlate (via aggregation, fusion) and mine collected information to discover knowledge and significant patterns?
- How to detect anomalous events (e.g., security threats), isolate them and control their spread dynamics?
- How to find hidden patterns in seemingly unrelated events, in presence of local views only?
- How to ensure every point in the monitored area covered?
- How to trust aggregate information or decisions? How to minimize false alarms?
- How to make intelligent decisions in integrated, collaborative autonomous and scalable manner for security and safety services?

Dependability / Security Issues

- How to provide higher information assurance for accurate situation-awareness and better decision making?
  - How accurate is sensed data under uncertainty, weak battery?
  - How to sample sensors for desired information quality?
  - How to quantify (multi-modal) quality of context?
  - How to improve reliability and robustness of sensor networks?
  - How to protect privacy of collected data or sensor locations?
  - How trustworthy is data stream: genuine, faulty, adversarial?
  - How to provide security against adversarial, replicate or malicious attacks?

Research Contributions

- Rich mathematical models and frameworks for multi-level security in pervasive wireless sensor networks

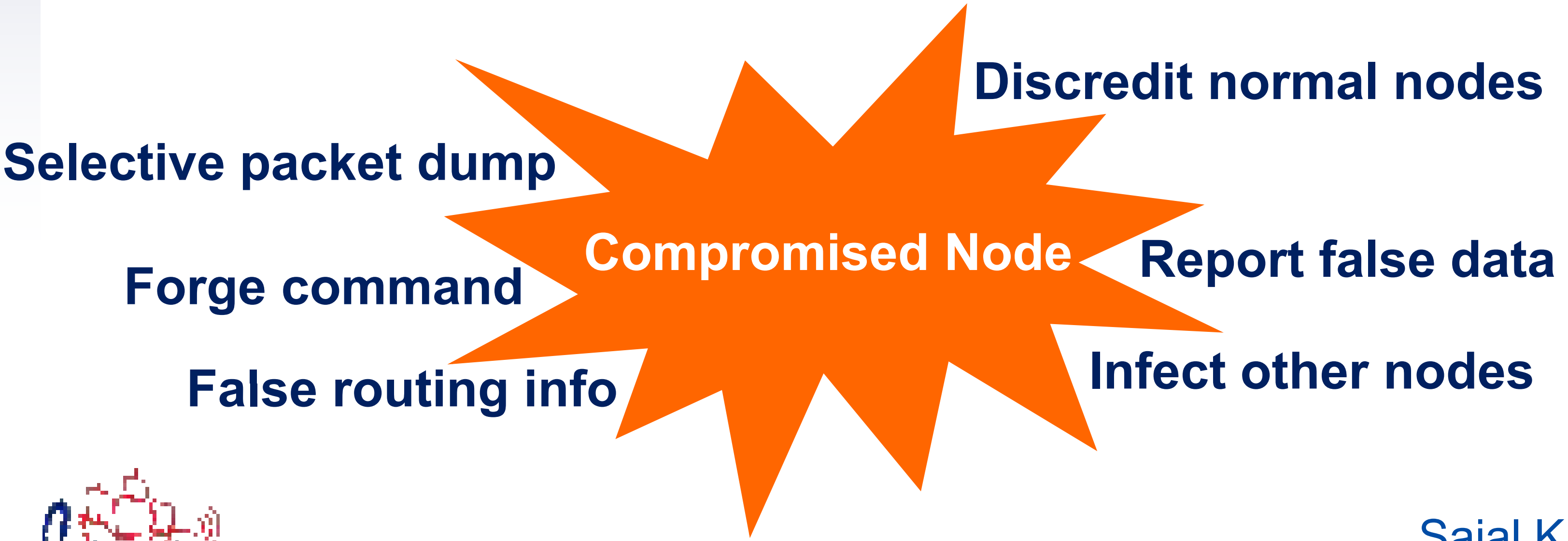
  - Distributed key management (among a cluster of nodes)

  - Secure information gathering, fusion, and routing

  - Model smart adversaries and situation-awareness

  - Detect anomalies – compromised and replicated nodes

  - Control propagation of internal attacks



Compromised Node

Discredit normal nodes

Selective packet dump

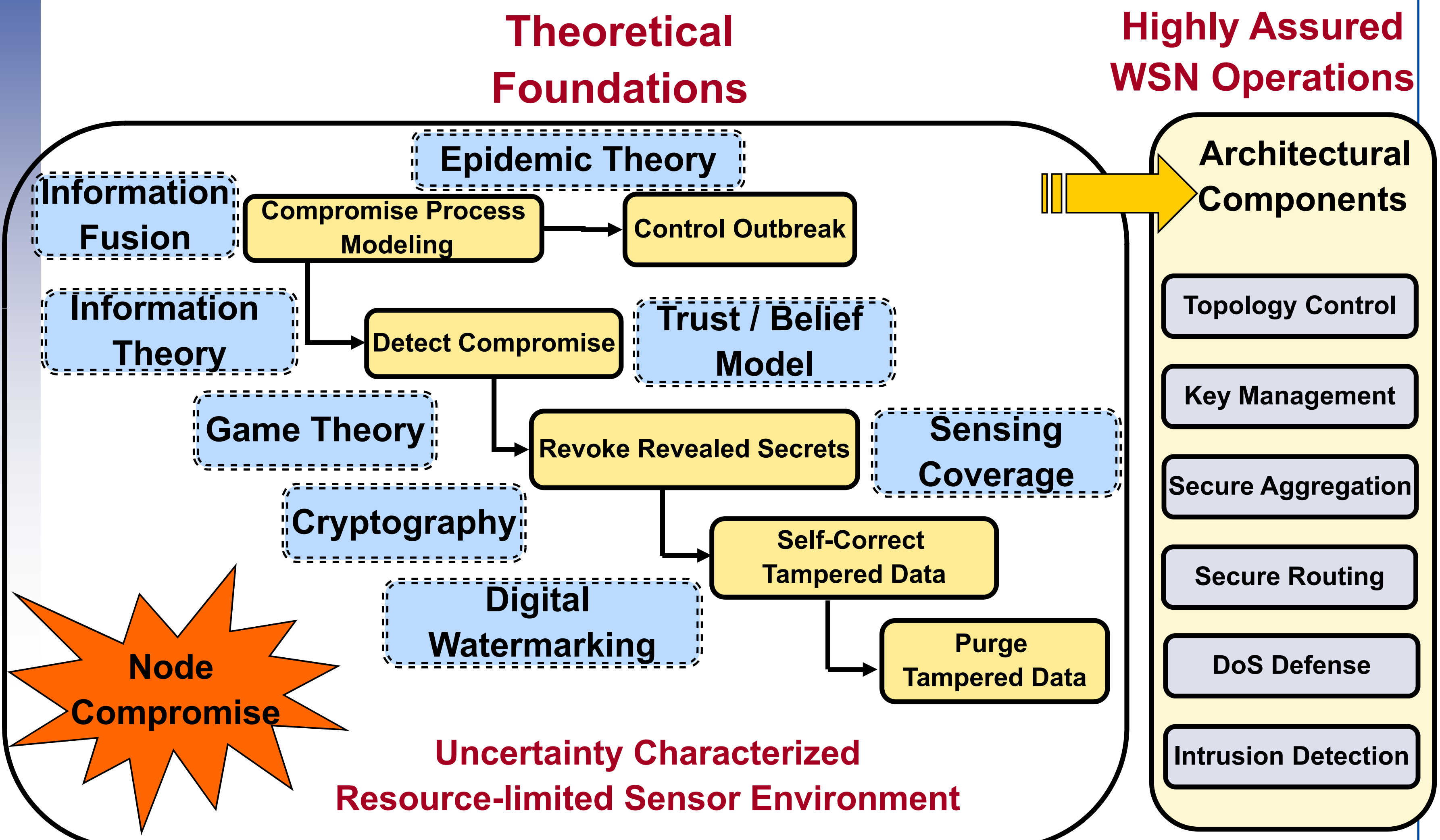
Report false data

Forge command

Infect other nodes

False routing info

Multi-Level Security Framework



Theoretical Foundations

Highly Assured WSN Operations

Epidemic Theory

Information Fusion

Information Theory

Game Theory

Cryptography

Digital Watermarking

Trust / Belief Model

Sensing Coverage

Compromise Process Modeling

Control Outbreak

Detect Compromise

Revoke Revealed Secrets

Self-Correct Tampered Data

Purge Tampered Data

Node Compromise

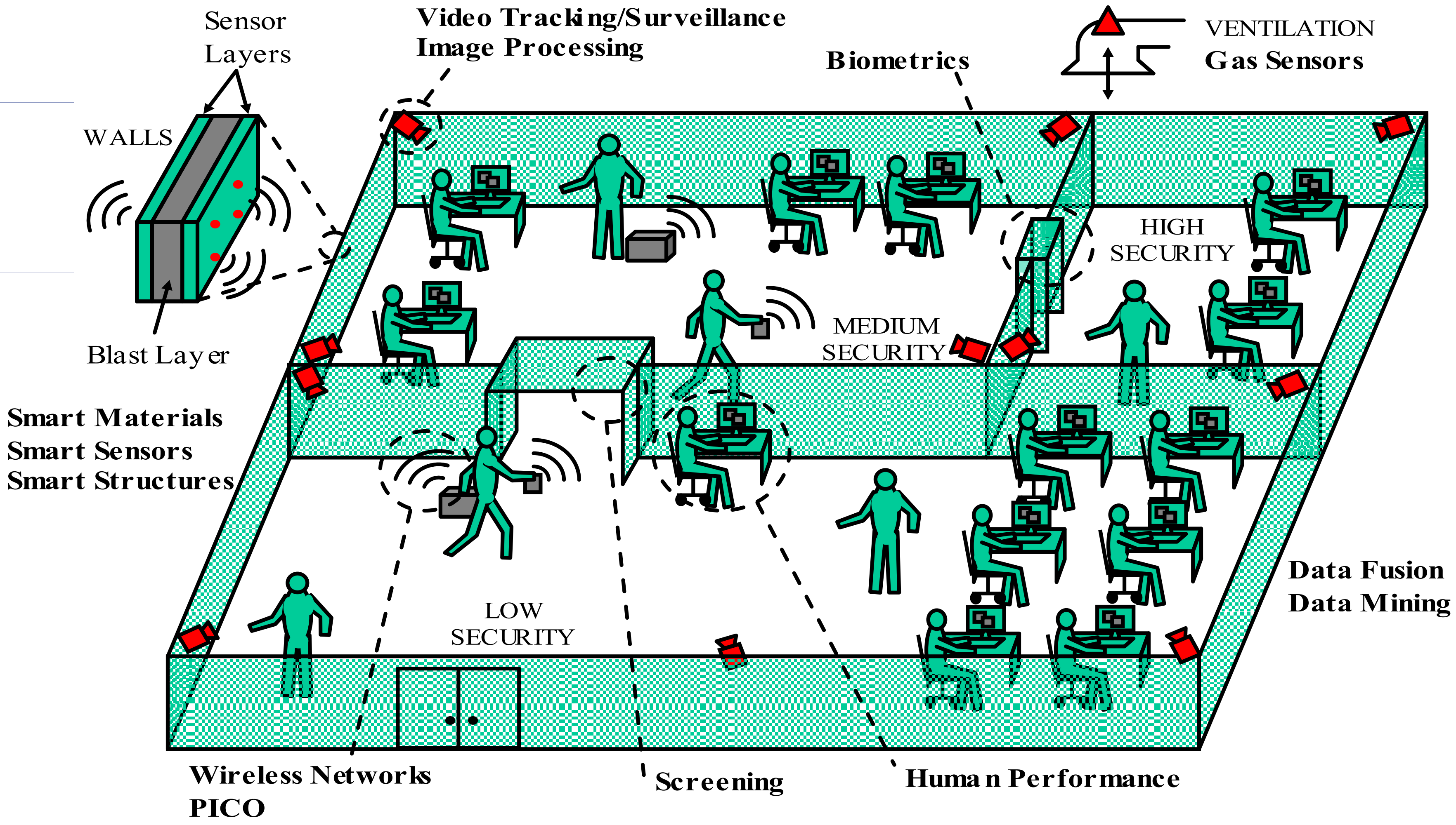
Uncertainty Characterized

Resource-limited Sensor Environment

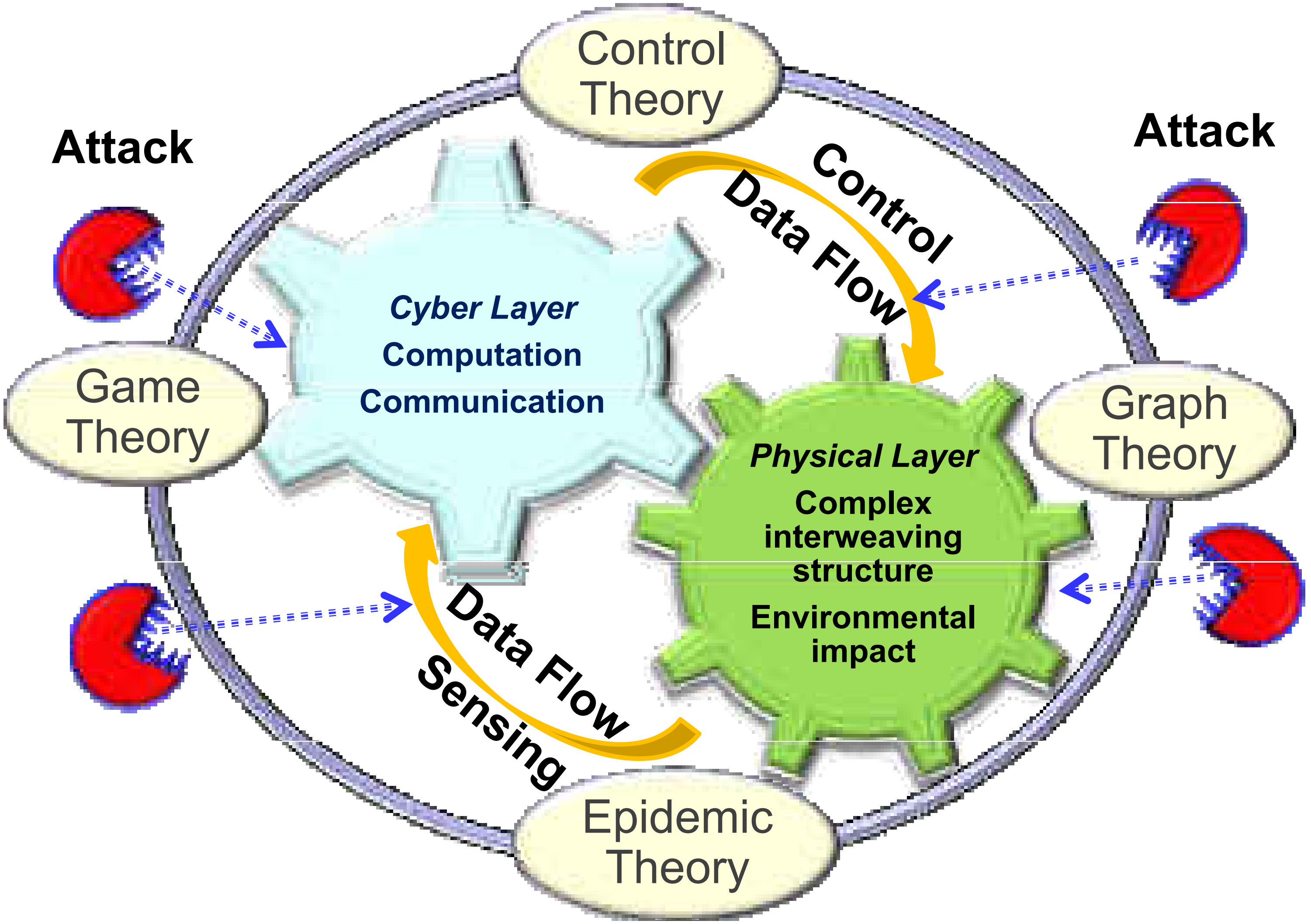
Architectural Components

- Topology Control
- Key Management
- Secure Aggregation
- Secure Routing
- DoS Defense
- Intrusion Detection

PSI Prototype



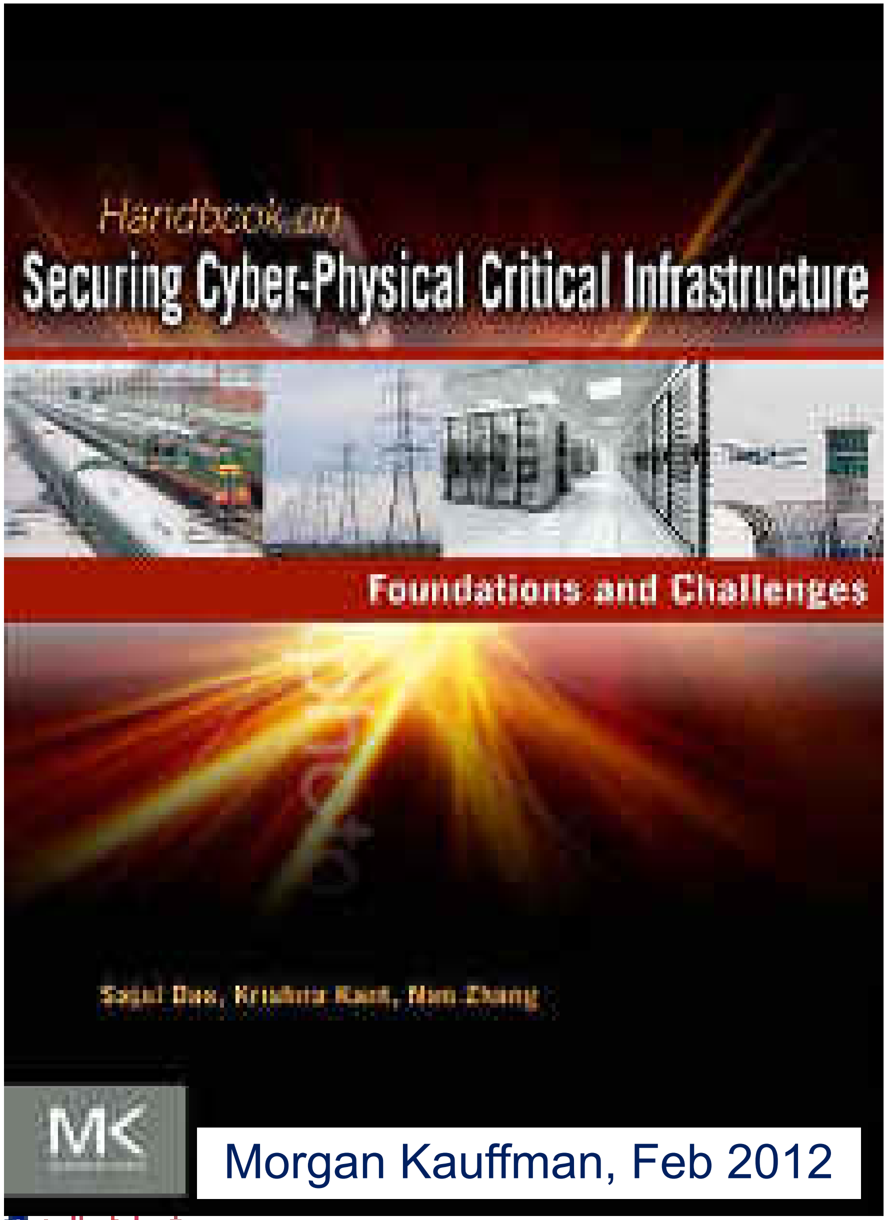
Foundations of CPS Security



S. K. Das, K. Kant, N. Zhang, *Handbook on Securing Cyber-Physical Critical Infrastructure*, Morgan Kaufmann, Feb 2012.

M. Xue, S. Roy, S. K. Das, “Security and Discoverability of Spread Dynamics in Cyber-Physical Networks,” *IEEE Transactions on Parallel and Distributed Systems* (special issue on CPS), Sept 2012.

CPS Security



Morgan Kauffman, Feb 2012

Publications on WSN / CPS Security

Epidemic Theory:

- P. De, Y. Liu, S. K. Das, "An Epidemic Theoretic Framework for Vulnerability Analysis of Broadcast Protocols in Wireless Sensor Networks," *IEEE Trans. Mobile Computing,* 8(3): 413-425, Mar 2009.
- P. De, Y. Liu, and S. K. Das, "Deployment Aware Modeling of Node Compromise Spread in Sensor Networks," *ACM Trans. on Sensor Networks,* 5(3): 413-425, May 2009.
- P. De, Y. Liu and S. K. Das, "Energy Efficient Reprogramming of a Swarm of Mobile Sensors," *IEEE Trans. on Mobile Computing,* 9(5): 703-1718, May 2010. *(also, IEEE PerCom 2008)*

Information-Theoretic Trust Model:

- Y. Sun, H. Luo, and S. K. Das, "A Trust-based Framework for Fault-tolerant Data Aggregation in Wireless Multimedia Sensor Networks," *IEEE Trans. Dependable and Secure Computing,* 9(6): 785-797, Nov-Dec 2012.
- W. Zhang, S. K. Das, and Y. Liu, "A Trust Based Framework for Secure Aggregation in Wireless Sensor Networks," *IEEE SECON 2006.*

Game Theory:

- J.-W. Ho, M. Wright, and S. K. Das, "Fast Detection of Mobile Replica Node Attacks in Sensor Networks Using Sequential Hypothesis Testing," *IEEE Trans. Mobile Computing,* 10(6): 767-782, June 2011.
- J.-W. Ho, M. Wright, and S. K. Das, "Zone Trust: Fast Node Compromise Detection and Revocation in Sensor Networks," *IEEE Trans. Dependable and Secure Computing* (special issue on Learning and Games, Security), 9(4): 494-511, 2012.
- N. Zhang, W. Yu, X. Fu, and S. K. Das, "Maintaining Defender's Reputation in Anomaly Detection against Insider Attacks," *IEEE Trans. Systems, Man and Cybernetics*, 40(3): 597-611, June 2010.

Control Theory:

- M. Xue, S. Roy, and S. K. Das, "Security and Discoverability of Spread Dynamics in Cyber-Physical Networks," *IEEE Trans. Parallel and Distributed Systems* (CPS special issue), 23(9): 1694-1707, 2012.

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Lecture 10: Smart Environments

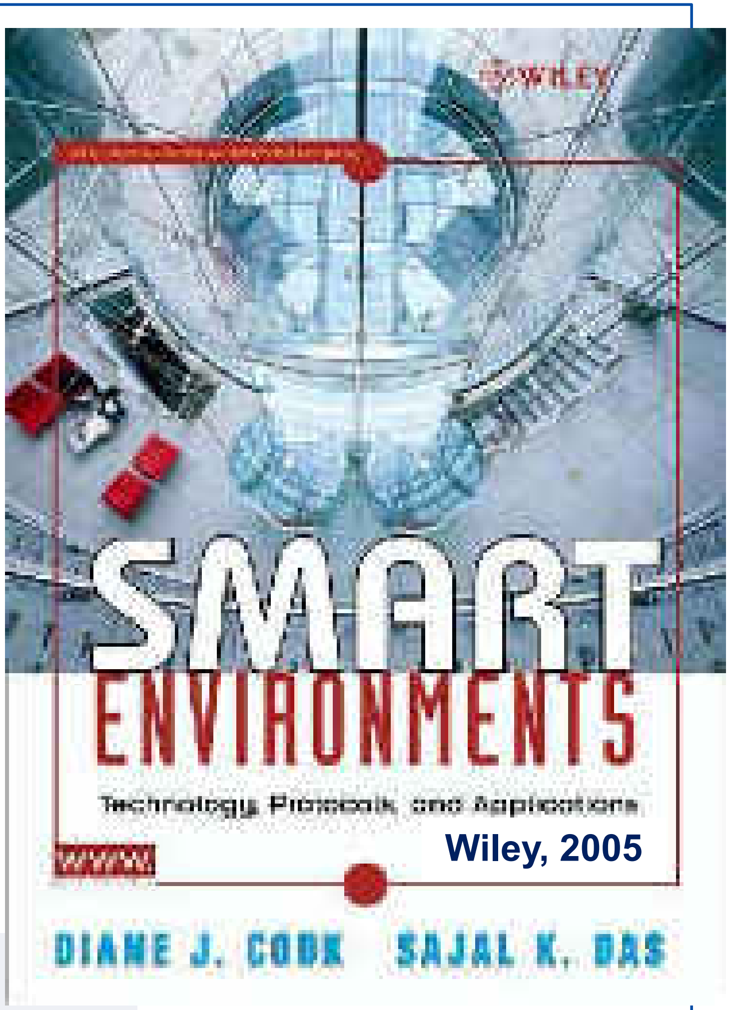
- ❑ Definition and Objectives
- ❑ Smart Home as a Rational Agent
- ❑ Fundamental Results
- ❑ Learning and Prediction based Design and Modeling
- ❑ Software Architecture
- ❑ Performance Study
- ❑ Video Demo
- ❑ References

Smart Environments

A Smart Environment is one that is able to autonomously *acquire* and *apply* knowledge about inhabitants and surroundings (environment), and *adapt* to improve experience *without explicit awareness*

Corollary: makes *intelligent decisions* in *automated, context-aware* manner → pervasive computing

- Context / Situation-awareness is the key



Wiley, 2005

Example Contexts:

- Mobility, Activity, Occupancy, Preferences, …
- Desire, Behavior, Mood, …

D. J. Cook and S.K. Das, “How Smart Are Our Environments? An Updated Look at State of the Art,” *Pervasive and Mobile Computing*, Vol. 3, No. 2, Mar. 2007.

Smart Home Objectives

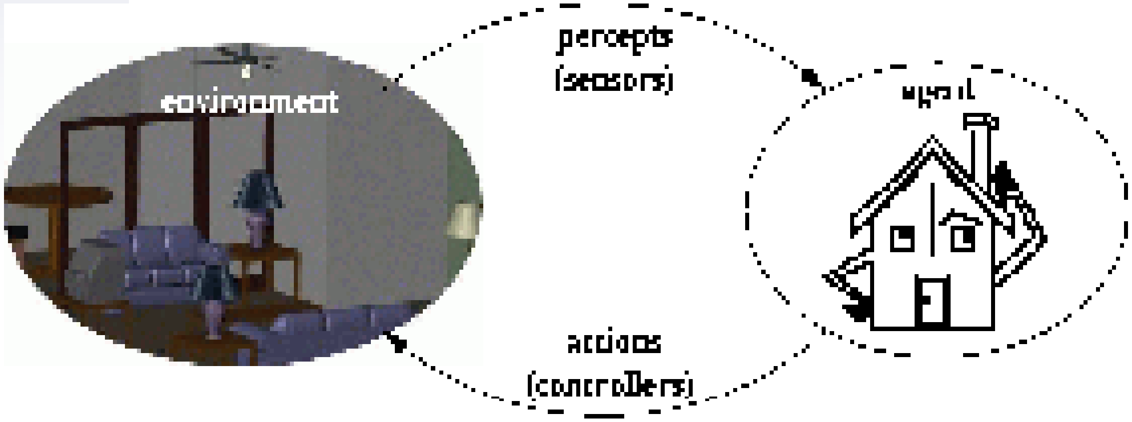
- Use smart and pro-active technology
  - Cognizant of inhabitant’s daily life and *contexts*
  - Absence of inhabitant’s explicit *awareness*
  - *Learning* and *prediction* as key components
  - Pervasive communications and computing capability

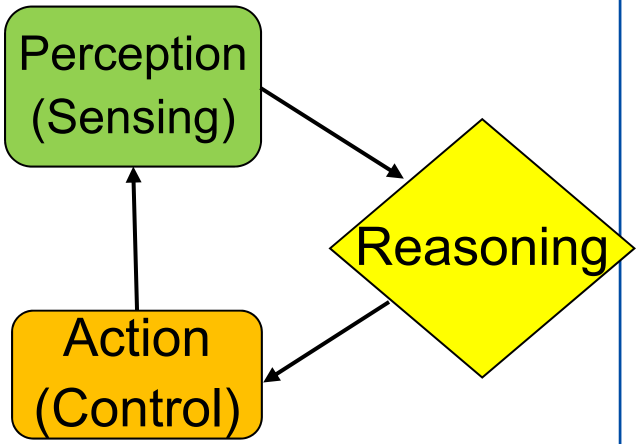
- Smart Environments Utility: Optimize goal functions
  - Minimize operation cost of managing home (e.g., proactive warning)
  - Minimize resource consumption (e.g., utility bills, network bandwidth)
  - Optimize automation of devices (i.e., reduction in manual operations)
  - Maximize security, …

- User Utility: Provide inhabitants with
  - Comfort : Reduction of inhabitant’s explicit activities
  - Productivity: Savings of inhabitant’s time

Smart Home as a Rational Agent

- *Perceive* the state of home via *sensors* and *acts* on environment via *actuators* (controllers)
- *Reasons* about and adapts to inhabitants, predicts context and makes *intelligent decisions*





Perception (Sensing)

Reasoning

Action (Control)

D. J. Cook and S.K. Das, "How Smart Are Our Environments? An Updated Look at the State of the Art," *Pervasive and Mobile Computing*, Vol. 3, No. 2, Mar. 2007.

Multi-Disciplinary Approach

- Monitoring, collection and fusion of context (sensory) data
- Active (streaming) databases and data mining
- Artificial intelligence, machine learning, decision making
- Model building – context, learning and prediction
- Online adaptive algorithms, Information theory, Game theory
- Wireless, mobile, and sensor networking
- Pervasive computing and communications
- Context-aware computing – resource management
- Middleware services, Autonomic management
- Cooperating agents and multi-agent communication
- Multimedia communication and entertainment
- Device automation, control and robotics
- Security, privacy and trust

Smart Environments: Challenges

- **Pattern Discovery**

  – How to learn inhabitant's lifestyle and contexts to identify spatio-temporal episodes? Anomaly detection?

- **Context- / Situation-awareness**

  – How to make predictive decisions, discover and provision for services and network resources in a pro-active manner?

- **Developing User Models**

  – How to build, customized (optimal, based on preferences) user models to guide automation and intelligence building?

- **Adapting the Automation**

  – How to improve and adapt the smart environment to suit lifestyle and goals of inhabitants with minimal, natural input?

Novel Methodologies Proposed

- Context Prediction: Learn and predict inhabitant's next (sequence of) contexts based on profile dictionary management and Lempel-Ziv compression (Active LeZi)
- Pattern / Episode Discovery: Mine inhabitant's contexts to discover spatio-temporal episodes in lifestyles (ED)
- User Models: Build optimal (customized) user models to guide automation and intelligence building (ProPHeT)
- Adapting the Automation: Refine the model for life-long learning and automation to adapt the environment to suit lifestyle and goals of inhabitants with minimal natural input

S. K. Das and D. J. Cook, "Designing Smart Home Environments: A Paradigm Based on Learning and Prediction," in *Wireless Mobile and Sensor Networks*, Wiley, 2006.

A. Roy, S. K. Das, and K, Basu, "A Predictive Framework for Location Aware Resource Management in Smart Homes," *IEEE Trans Mobile Computing*, 6(11):1270-1283, 2007.

Context Modeling and Prediction

Hypothesis

Inhabitant interactions in smart environments can be accurately automated through sensor observation and intelligent control using profile-based approach that automatically generates hierarchical inhabitant interaction models and learn decision policies.

➔ Inhabitant lifestyle has repetitive patterns that can be learned

→ Mobility and activity are piece-wise, stationary, stochastic processes with associated uncertainty, quantified by entropy.

→ Minimizing this uncertainty helps in accurate learning and prediction (estimation) of inhabitants' contexts.

A. Bhattacharya and S. K. Das, "LeZi-Update: An Information Theoretic Approach to Track the Mobile Users in PCS Networks", *ACM MobiCom'99*, Seattle, pp. 1-12, 1999 (Best Paper Award). *ACM Wireless Networks*, Vol. 8, Nos. 2-3, pp. 121-135, 2002.

Fundamental Result

Question: How to optimally track user context?

What is the minimum amount of information (measured in "bits") exchange to track user context, say mobility/activity?

Clue: The answer lies in the *randomness* of user contexts – the profile treated as a Piecewise, Stationary, Stochastic Process, *V*.

Lower Bound: *No mobility (context) tracking algorithm spends fewer bits per symbol than the entropy rate, H(V), associated with mobility.*

A. Bhattacharya and S. K. Das, "LeZi-Update: An Information Theoretic Approach to Track the Mobile Users in PCS Networks", *ACM MobiCom'99*, pp. 1-12, 1999 (Best Paper Award). Extended version *ACM Wireless Networks*, 8(2-3): 121-135, 2002.

A. Roy, A. Misra, and S. K. Das, "Location Update vs. Paging Trade-off in Cellular Networks: A VQ-based Approach," *IEEE Transactions on Mobile Computing*, 6(12):1426-1440, Dec 2007.

A. Misra, A. Roy and S. K. Das, "Information-Theory Based Optimal Location Management Schemes for Integrated Multi-System Wireless Networks," *IEEE/ACM Trans. on Networking*, 16(3): 525-538, June 2008.

Major Contributions: Single Inhabitant

- Optimal Tracking of User Contexts: A Predictive Framework based on Information Theory
  - Contexts captured as spatio-temporal samples of sensors (symbolic representation)
  - Use observed history profile to learn & predict next context(s) with high probability. Profile stored in compressed dictionary (Lempel-Ziv)
  - Customized models: higher-order statistics converge to optimal predictor
  - Derive bounds on context tracking (e.g., mobility)
- Context-aware (Predictive) Computing
  - Minimize resource consumption and optimize device automation
  - Reduce inhabitant's explicit activities, increase comfort, save time

S. K. Das et al., "A Predictive Framework for Location Aware Resource Management in Smart Homes", *IEEE PerCom 2003. (IEEE Transactions on Mobile Computing, 2007).*

Context Prediction: Active LeZi

- Use observed history to predict next context or sequence of contexts
- Based on Lempel-Ziv text compression algorithm
  - Parse string x_1, x_2, … into sub-strings w_1, w_2, … such that all but the last character of w_j is equal to some w_i for $1 < i < j$
  - Store sub-strings with frequency information in a trie
- Use moving window so information is not lost across phrase boundaries
- Given current state and recent history, predict next action with highest probability
  - Prediction by Partial Match (PPM) combines evidence from multiple context sizes
  - Higher order Markov model converges to an optimal predictor

Pattern Identification and Prediction

- Hypothesis: Users tend to exhibit common interaction patterns

Example: Most recent sequence of inhabitant actions:

{*AlarmOff, BedroomLightOn, CoffeeMakerOn, BathrommLightOn, BathroomVideoOn*}

- Learn patterns or *episodes* like (*BathroomVideoOn, action*), with greatest probability and output the corresponding action as its prediction
- Prediction by Markov Decision Process (MDP), Compression, Pattern Matching, etc.
- Anomaly detection: Find events or patterns out of normal behavior, and thus suspicious

Episode Discovery (ED)

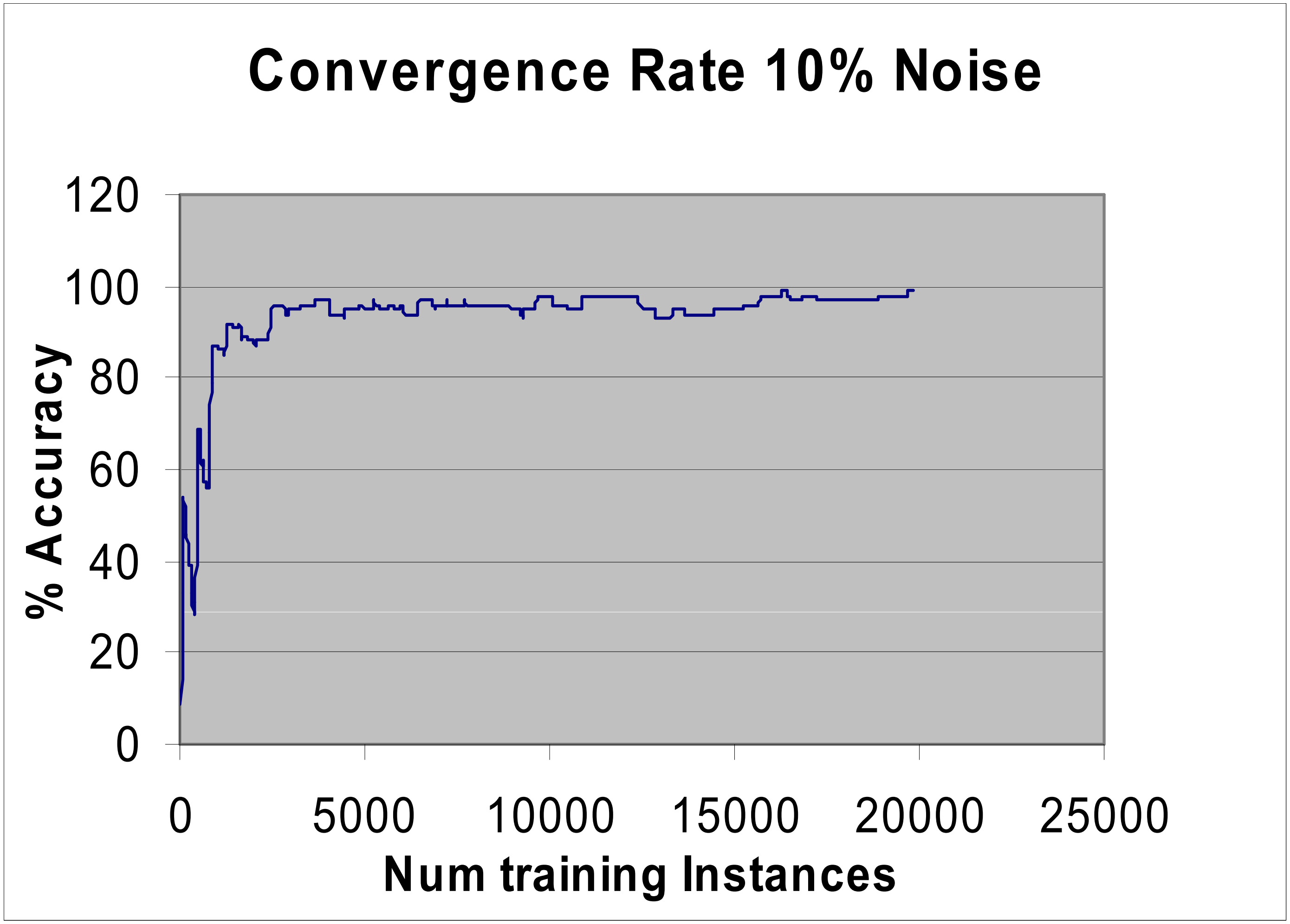
- Mine sequences from observation data
  - Episodes represent inhabitant tasks (e.g., grooming, cooking breakfast, cleaning, playing with kids)
  - Analyze lifestyle patterns
  - Discover significant repetitive sequences in action history
  - Decide what to predict and automate, aid decision learning
- Candidate sequences generated in time window moving over data, and evaluated using *maximum description length* (MDL) principle
- Features
  - Balances Frequency, Length of pattern, Periodicity
  - Real time processing
  - Provide probabilistic membership values
  - Hierarchical discovery of patterns
  - Detect concept drift

Evaluation of ED

Scenario	1	2	3	4	5
Events	12958	12884	12848	13058	12668
Periodic Episodes	13	13	13	13	13
IPAM Percentage Correct	39%	42%	43%	40%	41%
IPAM+ED Percentage Correct	77%	84%	69%	73%	65%
BPNN Percentage Correct	62%	64%	66%	62%	64%
BPNN+ED Percentage Correct	84%	88%	84%	84%	88%

ED improves performance by at least 20%

ALZ Performance: Synthetic Data



- ALZ input with state description, 85 - 96% accuracy
- ED + ALZ improves performance by 14%

Role of Prediction Algorithms

Learn and Predict

- Device and user interaction patterns
- Inhabitant's contexts (location, activity)

Episode Discovery (ED)

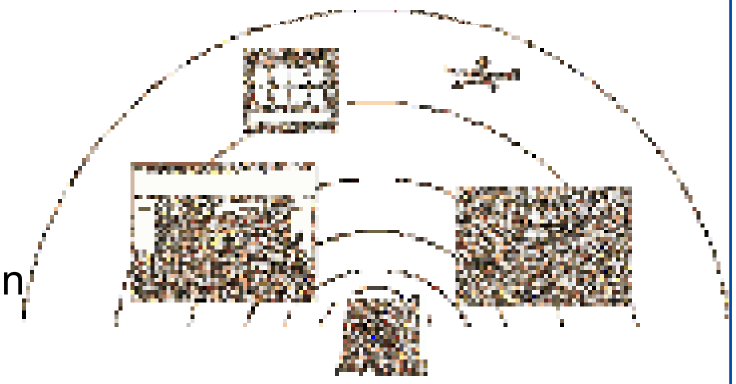
- Discover significant repetitive sequences in action history
- Decide what to predict and automate

Active LeZi Update (ALZ)

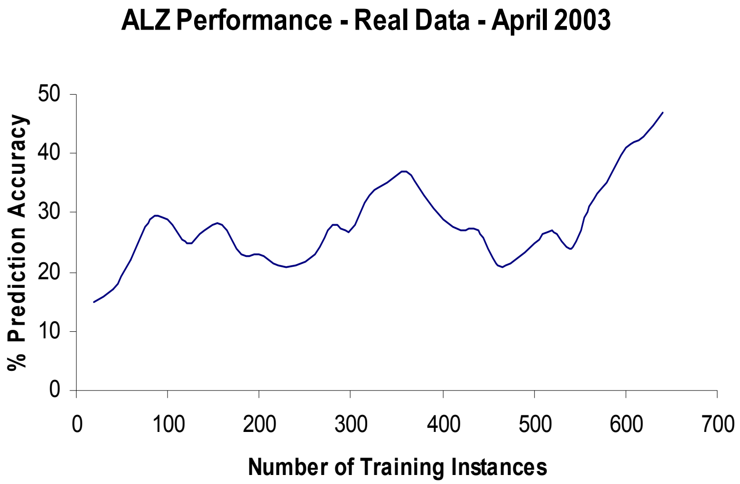
- Build history of observed actions to predict next action, or sequences of activities
- Based upon Lempel-Ziv (LZ78) text compression algorithm
- About 85% accuracy
- ED improves performance by 14%

Decision Maker (ProPHeT)

- Use delayed rewards
- Learn actions that yield greatest payoff
- ALZ input with state description
- ED helps segment and scale algorithm



Which device to use?



Performance on real MavHome data

Context Prediction Algorithm

Encoder: Collect and store symbols in compressed dictionary

Decoder: Decode encoded symbols, update phrase frequencies

Encoder (Compressor)

```
Initialize dictionary, phrase w
loop
  wait for next symbol v
  if (w.v in dictionary)
      w := w.v
  else
      encode < index(w), v >
   add w.v to dictionary
   w := null
forever
```

Decoder (Decompressor)

```
Initialize dictionary := empty
loop
   wait for next codeword < i, s >
   decode phrase := dictionary[i].s
   add phrase to dictionary
   increment frequency of every prefix
              of every suffix of phrase
forever
```

Complexity of Mobility Prediction

- *Minimizes entropy,* outperforms any *finite-order model*
- Optimal and adaptive to entropy rate with probability 1 is

$$\lim_{n \to \infty} \sup \frac{1}{n}\left[len\left(V_1, V_2, \ldots, V_n\right)\right] = H\left(\mathcal{V}\right)$$

- Dictionary size (Number of parsed phrases):

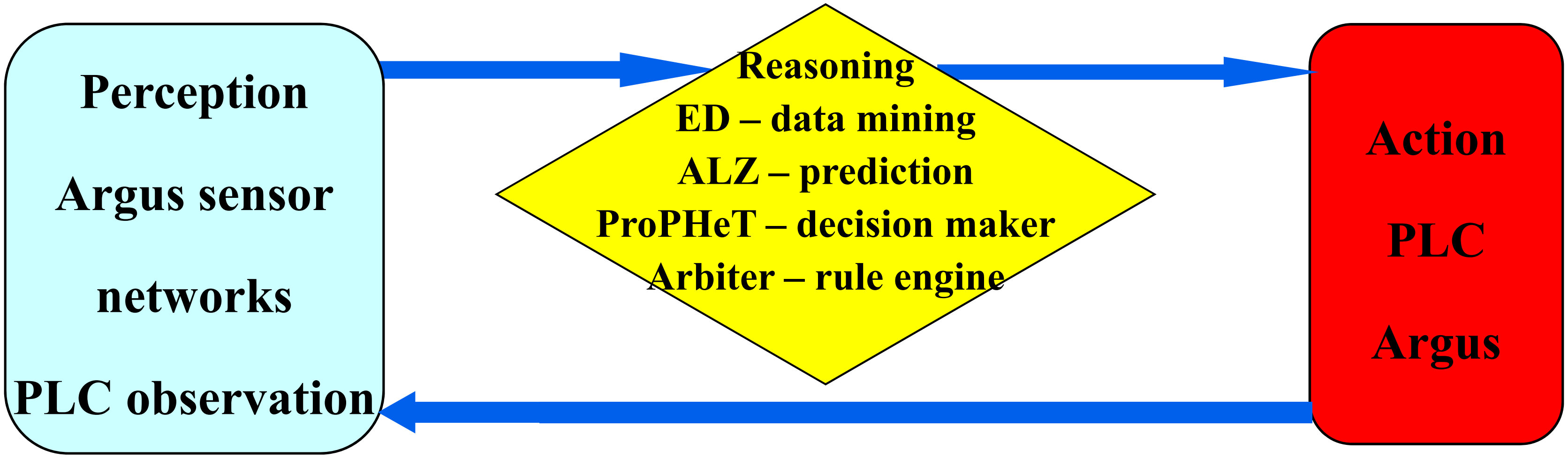
n : # of sensors

$$c(n) = O\left(\frac{n}{\log n - \log\log n}\right)$$

- Effective order Markov model (higher order statistics):

$$k = O\left(\log c\left(n\right)\right) = O\left(\log n - \log\log n\right)$$

MavHome Architecture



Perception

Argus sensor networks

PLC observation

Reasoning

ED – data mining

ALZ – prediction

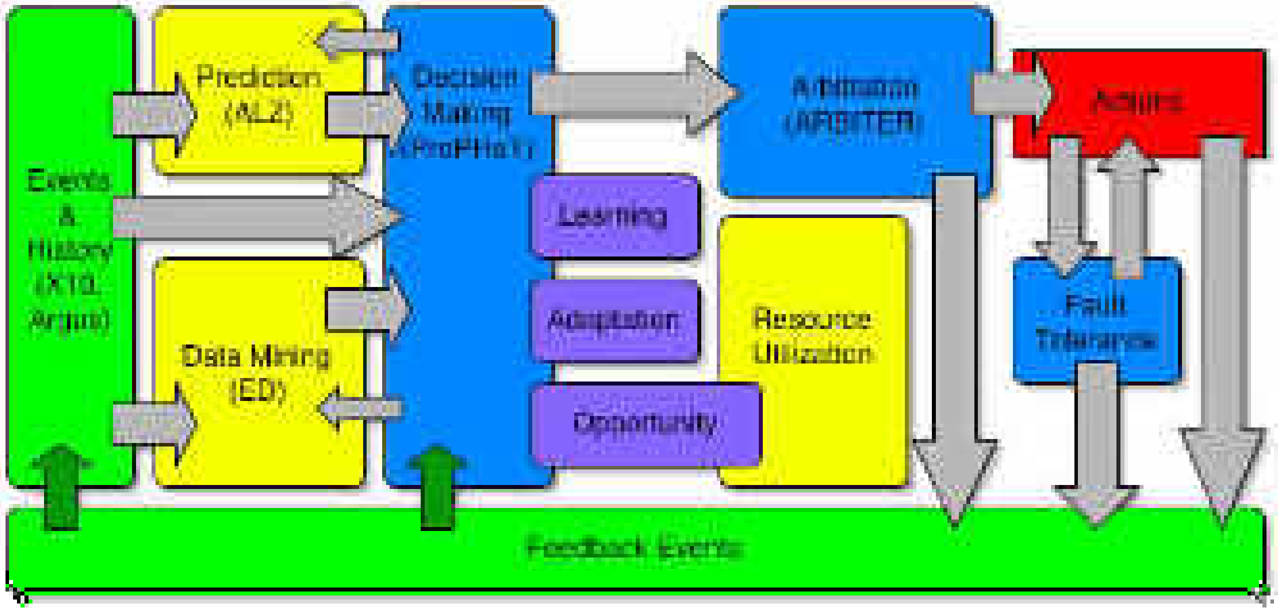
ProPHeT – decision maker

Arbiter – rule engine

Action

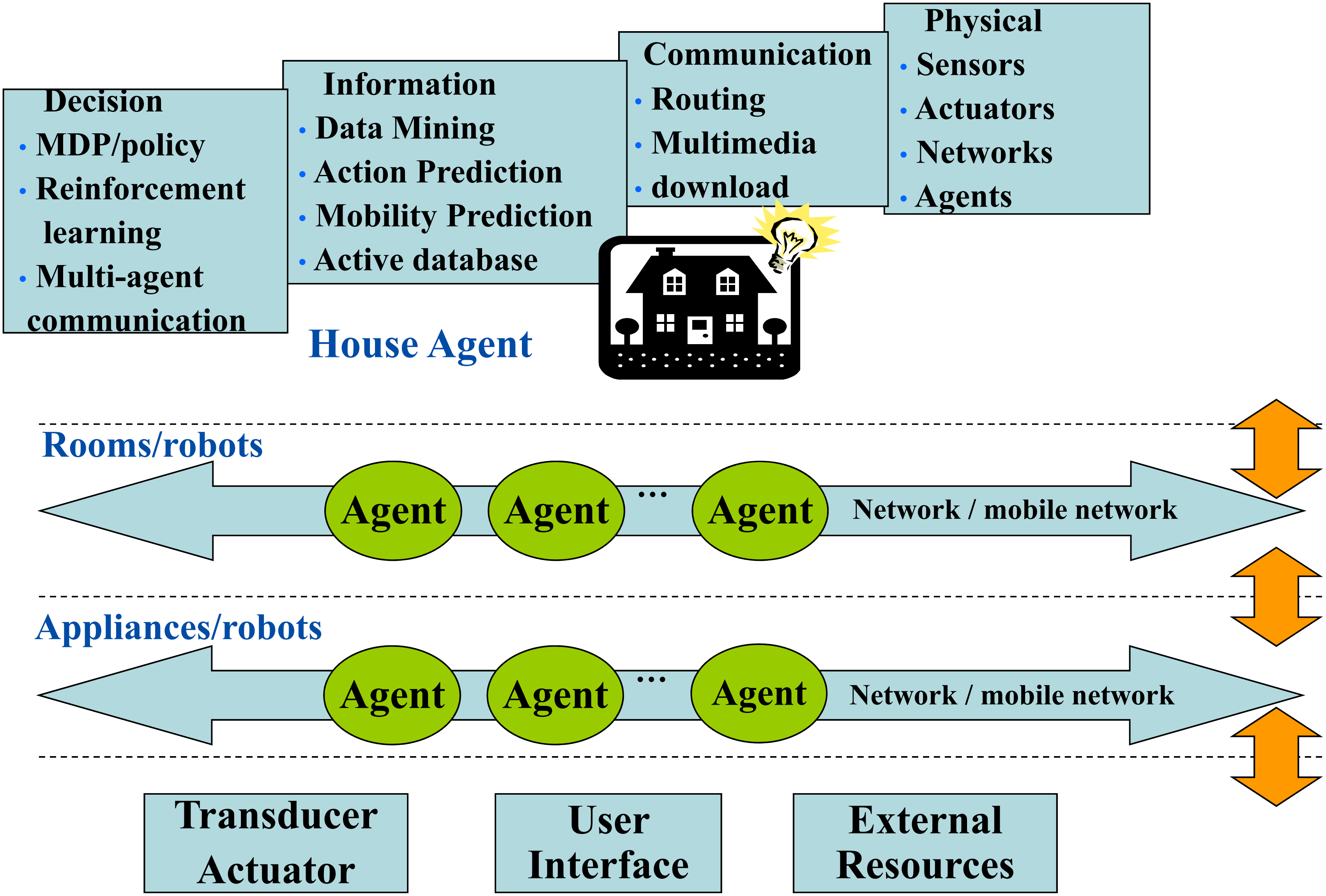
PLC

Argus



D. Cook, M. Youngblood, and S. K. Das, "A Multi-Agent Approach to Controlling a Smart Environment," In: *Designing Smart Homes* (Ed: J. Augusto),Springer, pp. 165-182, 2006.

MavHome Architecture



Decision
- MDP/policy
- Reinforcement learning
- Multi-agent communication

Information
- Data Mining
- Action Prediction
- Mobility Prediction
- Active database

Communication
- Routing
- Multimedia
- download

Physical
- Sensors
- Actuators
- Networks
- Agents

House Agent

Rooms/robots

Agent Agent … Agent Network / mobile network

Appliances/robots

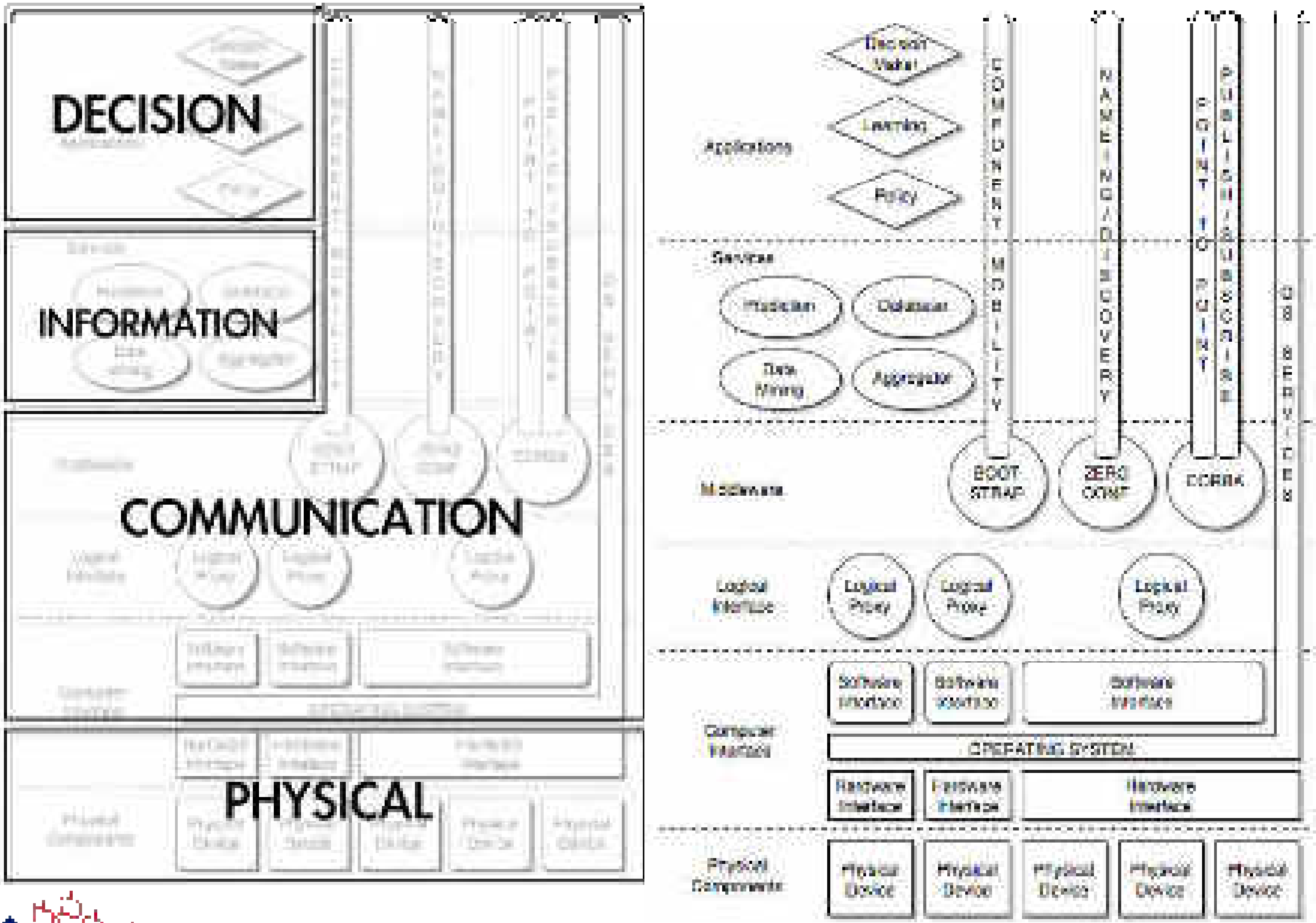
Agent Agent … Agent Network / mobile network

Transducer Actuator

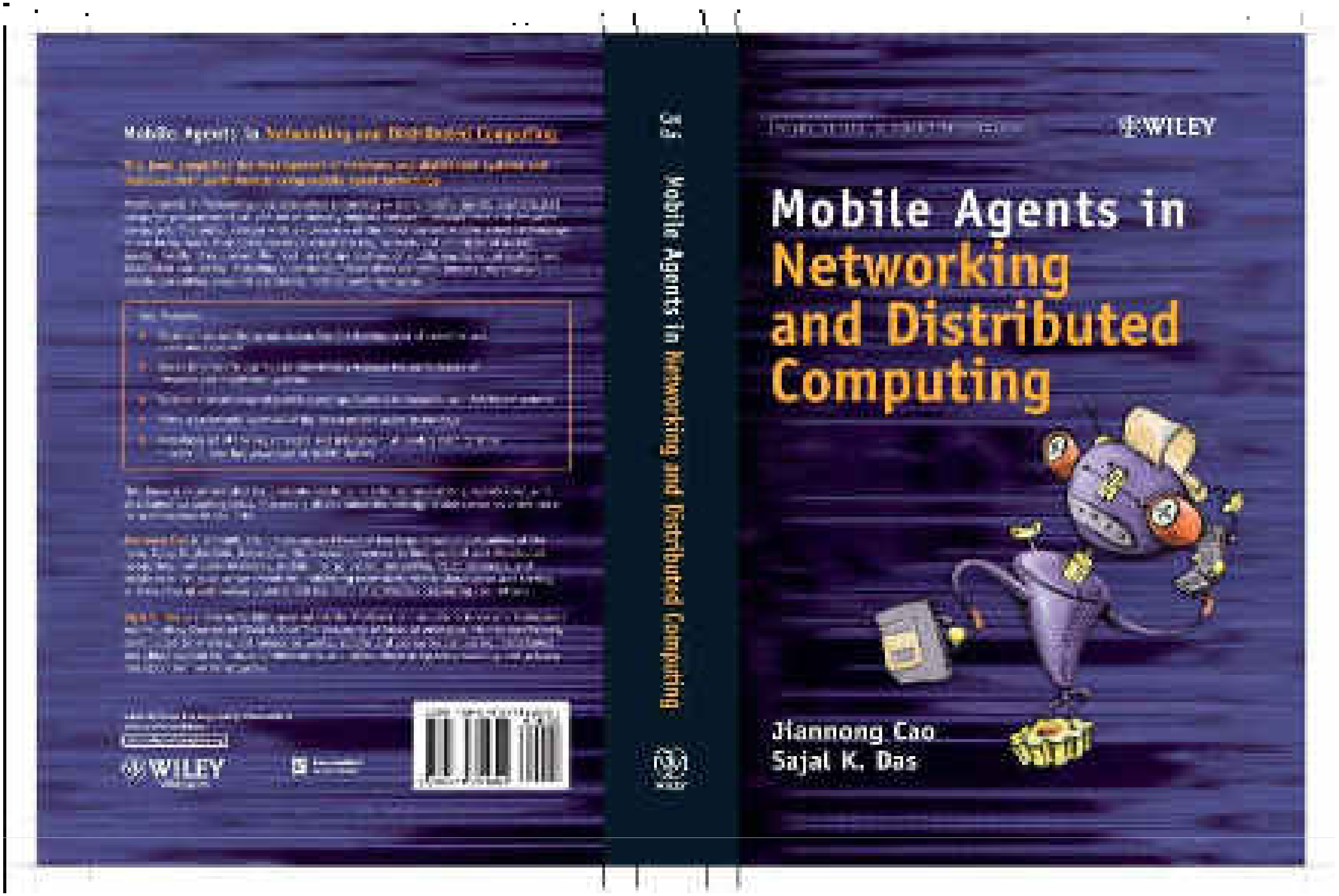
User Interface

External Resources

Middleware Architecture



Published July 2012

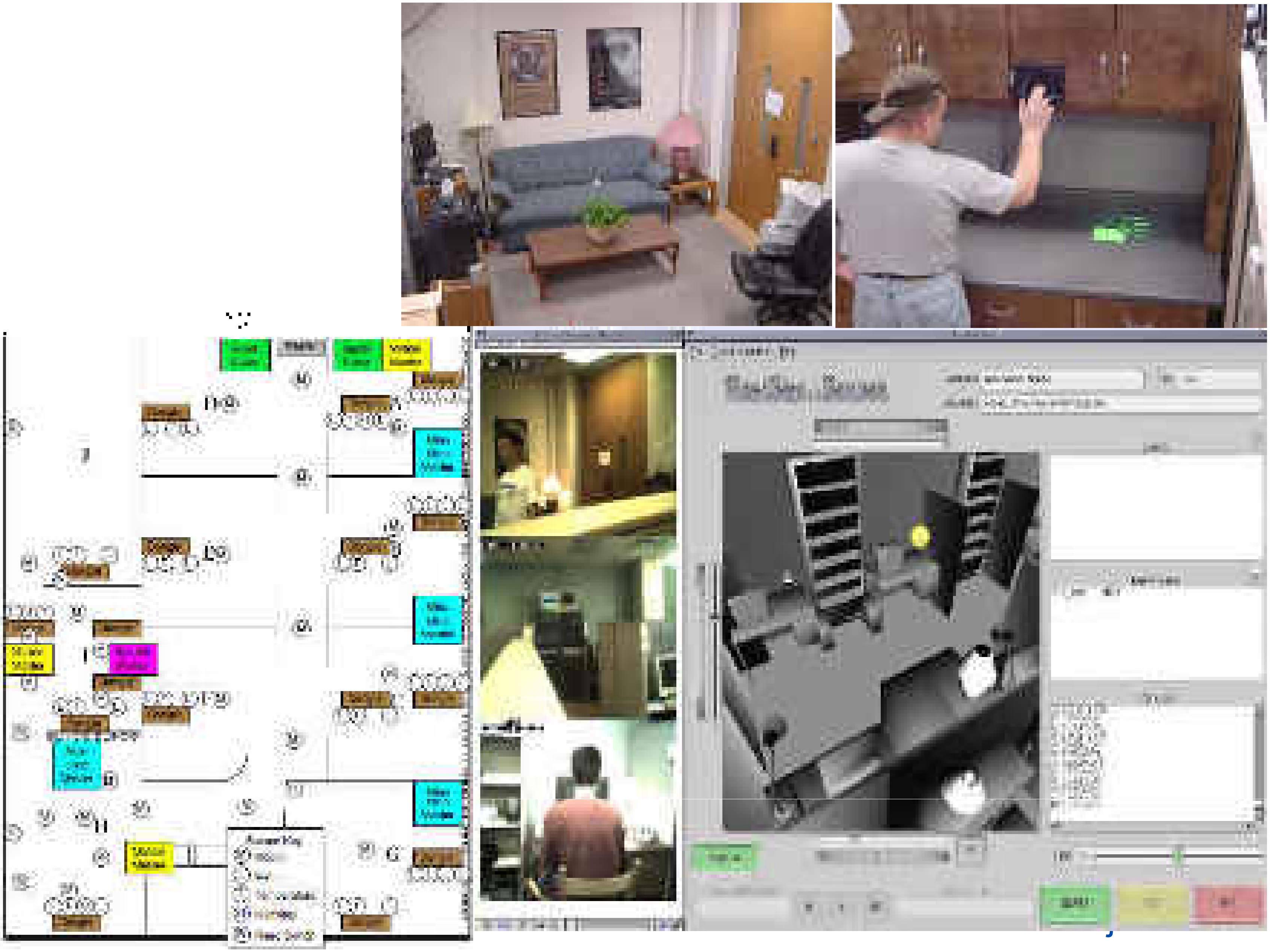


WILEY

Mobile Agents in Networking and Distributed Computing

Jiannong Cao
Sajal K. Das

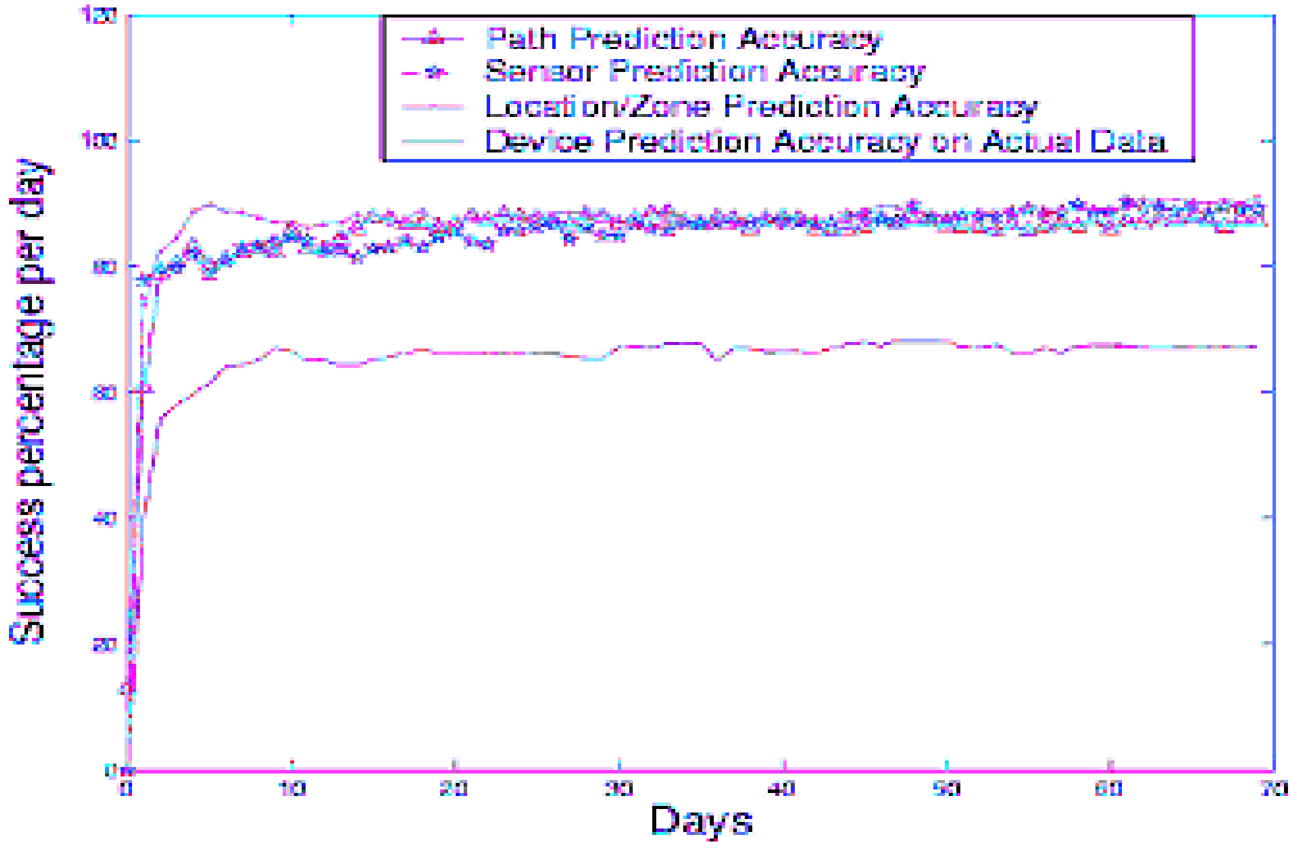
MavLab



Prediction Granularities

- Predicting next zone
  - Inhabitant’s immediate next zone / location
  - A coarse level movement pattern in different locations
- Predicting typical routes / paths
  - Inhabitant’s typical routes along with zones
  - More granular indicating inhabitant’s movement patterns
- Predicting next sensor
  - Every next sensor predicted from current sensor
  - Large number of predictions lead to system overhead
- Predicting next device
  - Predict every next device the inhabitant is going to use
  - Details of inhabitant’s activities can be observed

Learning Curve & Predictive Accuracy



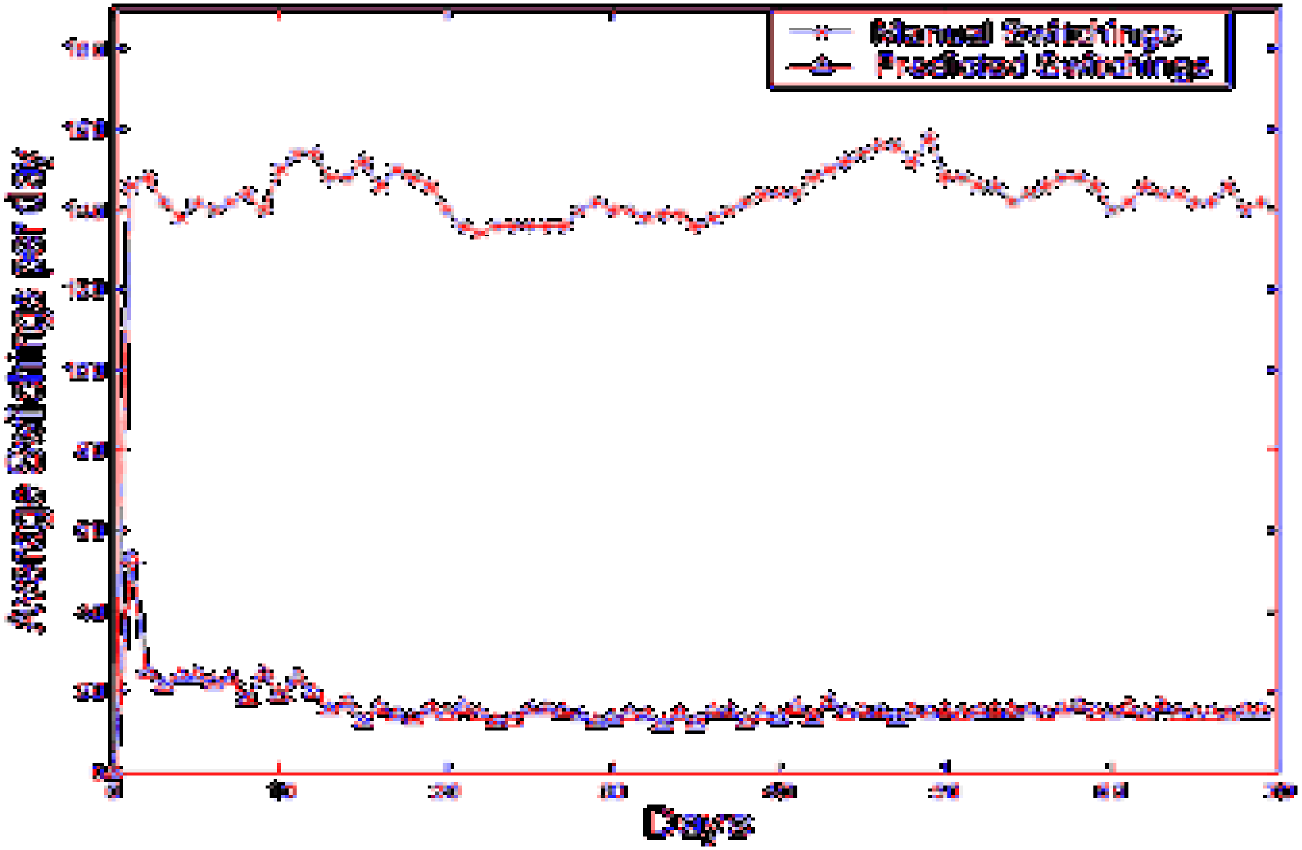
- 85% – 96% accuracy in predicting next sensor, zone, typical route
- Route prediction accuracy slightly lower than location prediction
- 4 - 6 days to learn about inhabitant's life-style and movements
- Higher granularity keeps device prediction accuracy low (63%)

Sajal K. Das

Performance Study

- Goal functions (utility) for the environment
  - Minimize management cost, resource consumption (energy, bandwidth)
  - Optimize automation of devices – reduce manual control
  - Maximize security
  - Minimize anomaly
  - Reduce safety rule violations over time
- Inhabitants’ utility
  - Reduce explicit activities (Comfort)
  - Save time (Productivity)
  - Reduce violation of inhabitant rules over time

Reduction in Manual Operations

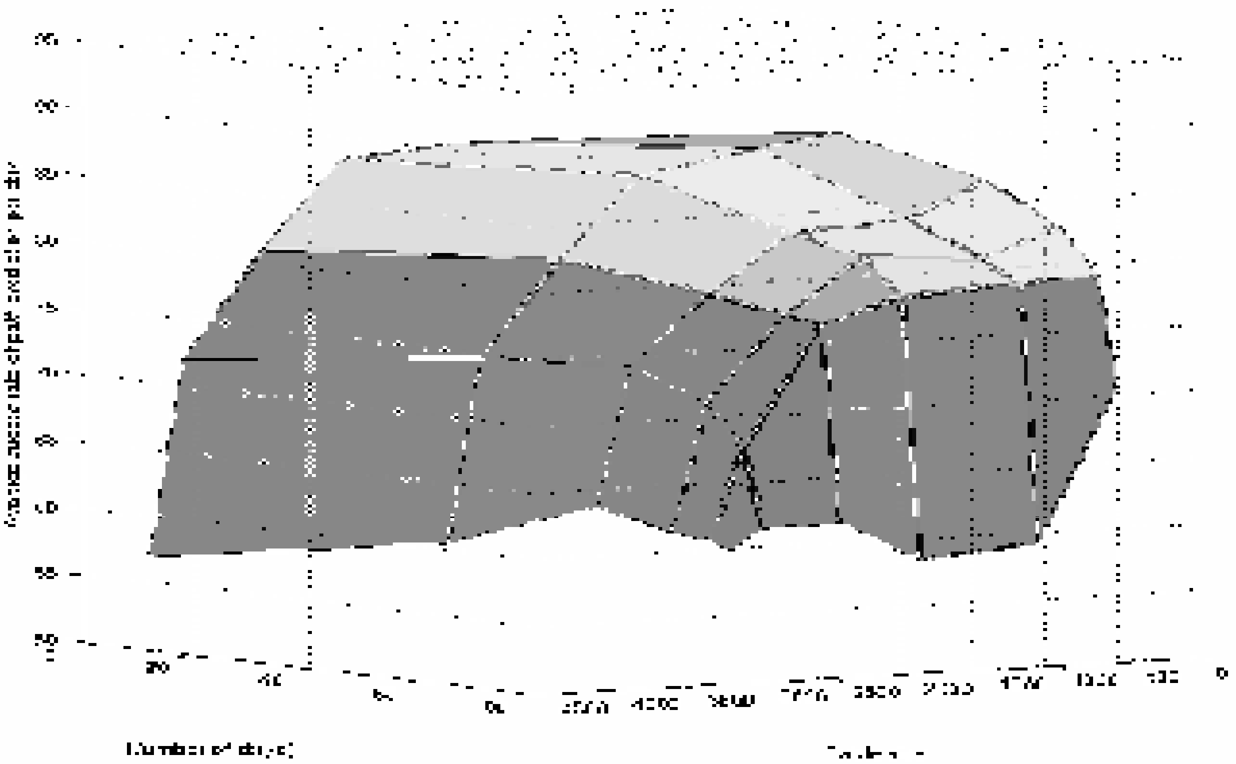


- Prediction accuracy → reduction in manual operations of devices → brings comfort and productivity, saves time

- 80% – 85% reduction in manual switching operations

Memory Requirements

Prediction success-rate vs. # of days vs. table-size



- 85% success rate require 3–4 KB memory for 180 days profile
- Typical routes are only 5% – 11% of total routes

Context-Aware Energy Management

- Static Scheme (Worst-case scenario):

  - Devices (lights, fan, air-conditioner, etc.) switched on for a fixed amount of time daily

- Optimal Scheme (Best-case):

  - Devices manually controlled and optimally used

- Predictive Scheme (Smart energy management):

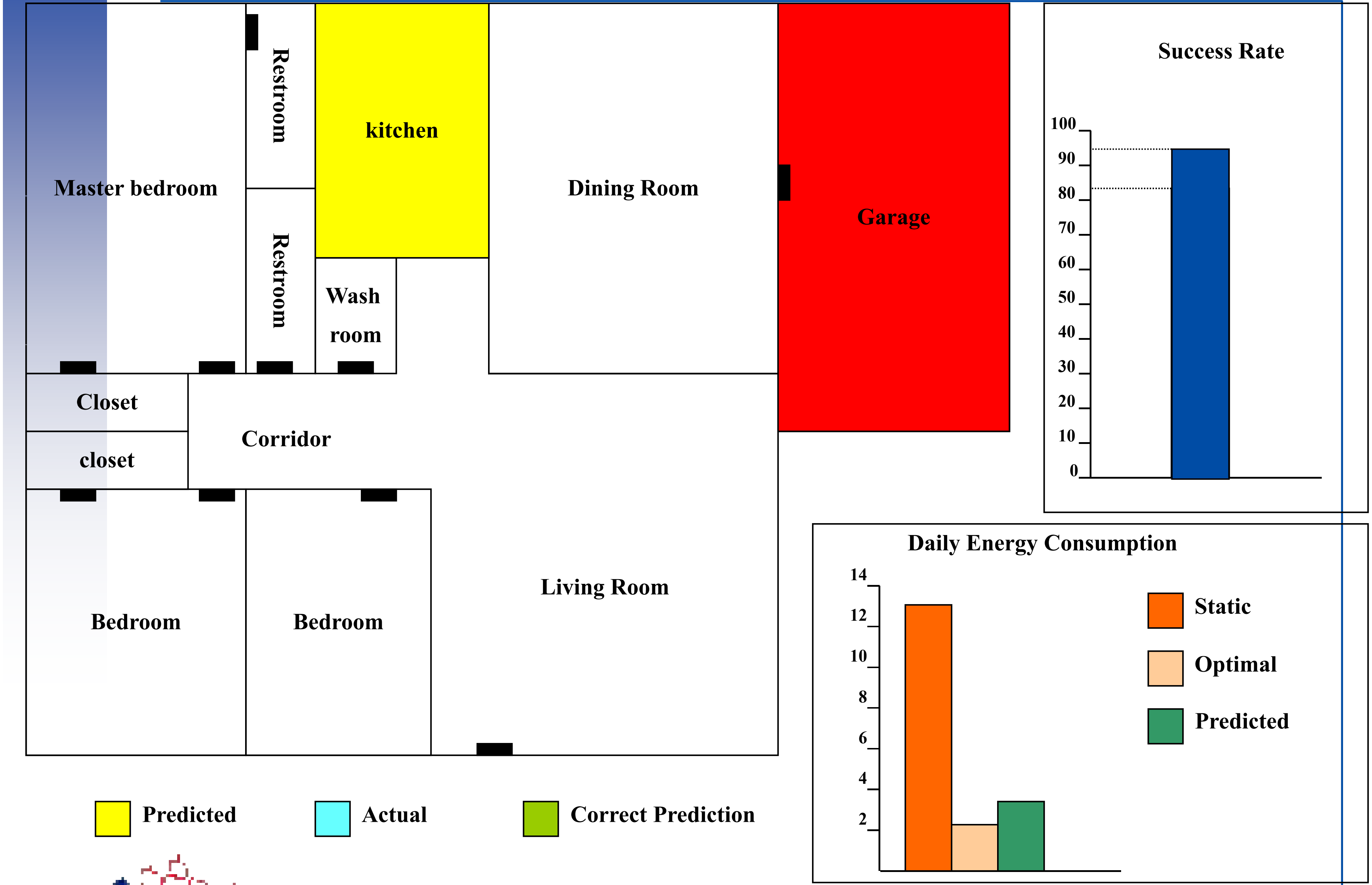
  - Devices operate in pro-active mode, based on predicted routes and activities

D. J. Cook and S. K. Das, "Modeling and Controlling Everyday Environments", 2007.

A. Roy, S. K. Das and A. Misra, "Exploiting Information Theory for Adaptive Mobility and Resource Management in Wireless Networks," *IEEE Wireless Communications* (Special Issue on Mobility and Resource Management), Vol. 11, No. 4, pp. 59-65, 2004.

A. Roy, S. K. Das, K. Basu, "Location Aware Resource Management in Smart Homes", *Proc. IEEE Int'l Conf. on Pervasive Computing,* pp. 481-488, 2003. *IEEE Transactions on Mobile Computing,* Vol. 6, No. 11, pp. 1270-1283, Nov 2007.

Snapshot of Simulation



Sajal K. Das

Challenges for Multiple Inhabitants

- Optimal tracking of multi-inhabitant contexts with conflicts
  - NP-hard problem due to correlations and dependencies among contexts
  - Minimize joint entropy for context uncertainties
- Satisfying inhabitants' preferences on activities
  - Resolve conflicts and achieve balance among activity preferences
- Cooperative learning – Game theoretic framework
  - Stochastic game theory based learner action algorithm, each inhabitant maintains beliefs about strategy of other inhabitants
  - An inhabitant predicts expected entropy of its action at any time
  - Vary learning rate to accelerate convergence to Nash Equilibrium.
  - Learn quickly (slowly) if predicting next state incorrectly (correctly)

N. Roy, A. Roy, and S. K. Das, "Context-Aware Resource Management in Multi-Inhabitant Smart Homes: A Nash H-Learning based Approach," *Proc. IEEE Conf Pervasive Computing*, 2006. (Mark Weiser Best Paper Award), *Pervasive and Mobile Computing*, 2(4): 372-404, Nov. 2006. *IEEE PerCom 2011*, *IEEE TMC 2012*.

Nash H-learning Framework

- Inhabitants want to satisfy own activity preferences

  - Selfish agents, suitable balance desired among preferences

- Non-cooperative (stochastic) game theory

  - Inhabitants are players and (conflicting) activities are strategies

- Decision making component of smart home

  - Don't mimic the actions
  - Learn to perform actions (Q-learning)

- Algorithm for learning a value function

  - Map state-action pairs to future discounted reward using entropy measure (denoted by H)

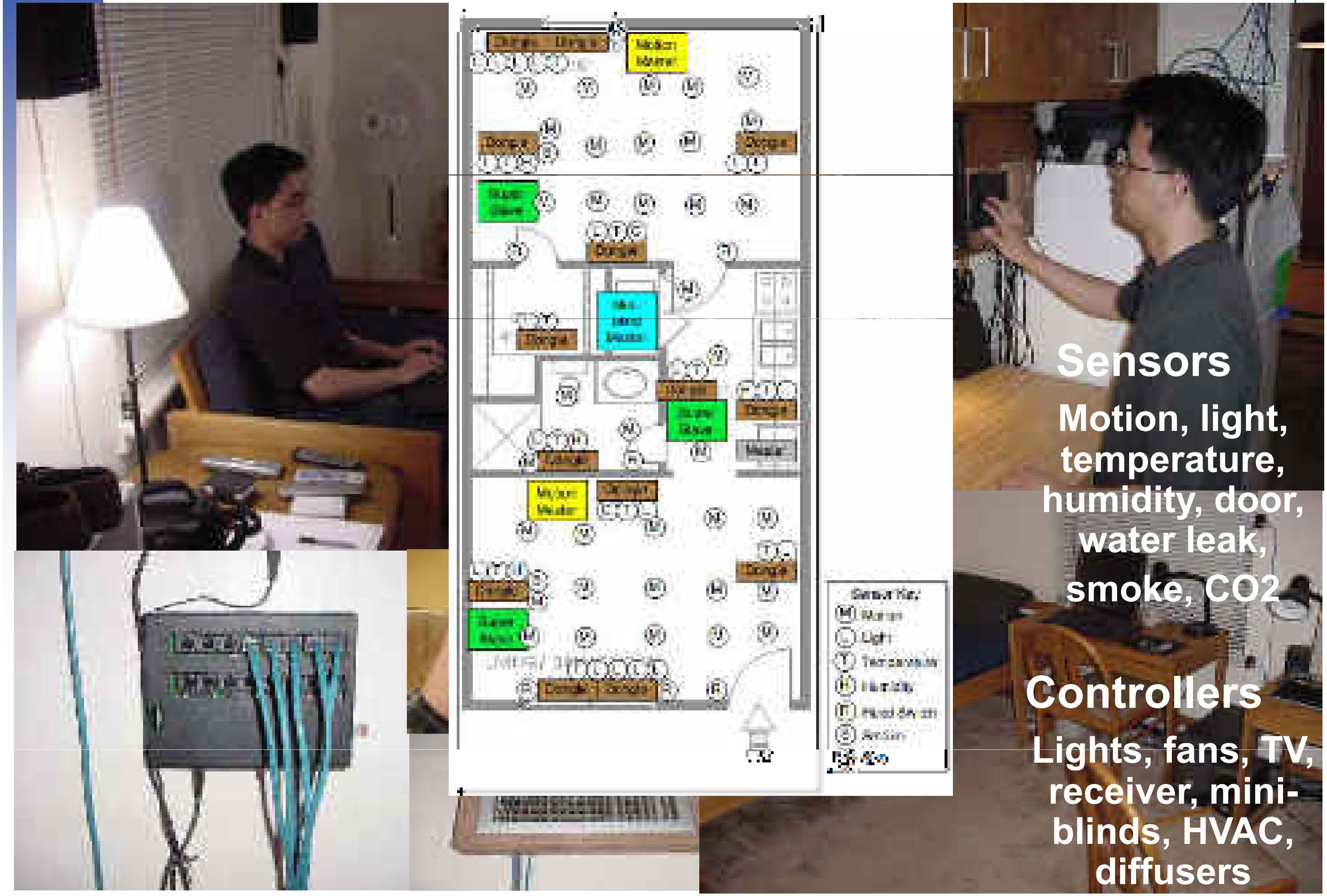
  - Satisfy Nash condition and minimize joint uncertainty

N. Roy, A. Roy, and S. K. Das, "Context-Aware Resource Management in Multi-Inhabitant Smart Homes: A Nash H-Learning based Approach," *Proc. IEEE Conf on Pervasive Computing* (PerCom), Mar 2006. (Mark Weiser Best Paper Award)

Extended version in *Pervasive and Mobile Computing*, 2(4): 372-404, Nov. 2006.

MavPad: Apartment in the Dorm

MavPad: Apartment in the Dorm



Sensors

Motion, light, temperature, humidity, door, water leak, smoke, CO2

Controllers

Lights, fans, TV, receiver, mini-blinds, HVAC, diffusers

Video Demo

Conclusions

User / Space	Homogeneous	Heterogeneous
Single Inhabitant	PerCom'03, IEEE TMC'07 (A. Roy, Das, et al.)	INFOCOM'04, IEEE ToN'08, HealthNet'09 (Misra, A. Roy, Das)
Multiple Inhabitants	PerCom'06, PMC'07, PMC'09 (N. Roy and Das)	QShine'09 (Best Paper) (N. Roy, Das, Julien)

- How to manage information and learn patterns across multiple contexts as inhabitants interact with *heterogeneous smart spaces*?

The same user behaves differently in different spaces.

User/Sensors	Single Context Attribute	Multiple Context Attribute
Single User	**MobiCom'99:** Bhattacharya, Das **PerCom 2003, TMC'07:** Das, et al. **Infocom 2004:** Misra, Das	**WiMob 2007:** Roy, Das **HealthNet 2008:** Roy, Das **PMC 2009:** Roy, Das, et al.
Multiple Users	**PerCom 2006, PMC'07:** Roy, Das **MobiQuitous 2009:** Roy, Das **ICOST 2005:** Roy, Das	**IEEE PerCom 2011:** Roy, Das, et al. **IEEE TMC 2012:** Roy, Das, Julien

Ongoing Work

- Dynamically build Smart Communities (cooperative vs. competing smart spaces) to execute multiple missions.
- Security, privacy and trust management.
- Seamless context recognition when users move across multiple smart space boundaries.
- Figure of merit to compare smart spaces.
- Use smart environment as a mechanism to influence change in user behavior – study effect on psychology of activity patterns, mood, health, mind.
- Psychological and Sociological dynamics and impact.

Publications in Smart Environments

- S. K. Das, D. J. Cook, A. Bhattacharya, E. Heierman, and J. Lin, "The Role of Prediction Algorithms in the MavHome Smart Home Architecture," *IEEE Wireless Communications*, 9(6): 77-84, Dec 2002.
- D. J. Cook and S. K. Das, *Smart Environments: Technology, Protocols and Applications*, John Wiley, 2005.
- S. K. Das, N. Roy and A. Roy, "Context-Aware Resource Management in Multi-Inhabitant Smart Homes: A Framework Based on Nash H-Learning," *Pervasive and Mobile Computing,* 2(4): 372-404, Nov. 2006. (Best Paper, IEEE PerCom 2006)
- D. J. Cook and S. K. Das, "How Smart Are Our Environments? An Updated Look at the State of the Art," *Pervasive and Mobile Computing* (Special Issue on Smart Environments), 3(2): 53-73, Mar 2007.
- A. Roy, S. K. Das and K, Basu, "A Predictive Framework for Location Aware Resource Management in Smart Homes," *IEEE Transactions on Mobile Computing*, 6(11): 1270-1283, Nov 2007.
- D. De, S. Tang, W.-Z. Song, D. J. Cook, and S. K. Das, "ActiSen: Activity-aware Sensor Network in Smart Environments," *Pervasive and Mobile Computing*, 8(5): 711-731, Oct 2012.
- G. Ghidini, S. K. Das, and V. Gupta, "FuseViz: A Framework for Web-based Data Fusion and Visualization in Smart Environments," *Proc. IEEE Comference on Mobile Adhoc and Sensor Systems* (MASS), Las vegas, Nevada, Oct 2012.

Outline

- **June 18:**
  - Wireless Mobile Communications – Fundamentals
  - Cellular Concepts and Channel Assignment
  - Mobility Management and Mobile Internet
  - Resource Management and Wireless QoS
- **June 19:**
  - Wireless Sensor Networks (WSNs) – Fundamentals
  - Energy-Efficient Algorithms and Protocols for WSNs
  - Pervasive Computing and Cyber-Physical Systems
  - Security Solutions in WSNs
- **June 20:**
  - Smart Environments – Design and Modeling
  - Smart Healthcare – Middleware Services
  - Guidelines to Excellent Research
  - Mentoring and Value-Added Education

Lecture 11: Smart Healthcare

- Motivation and Scenario
- Pervasive Information Community Organization
- Middleware Challenges
- Multi-modal Sensing Framework
- Context Quality and Energy Trade-off
- Experimental Study
- References

Smart Health Care

Aging World Population

- By 2040, 23% US population 65+
- 9% of adults aged 65+ and 50% 0f adults aged 85+ need assistance

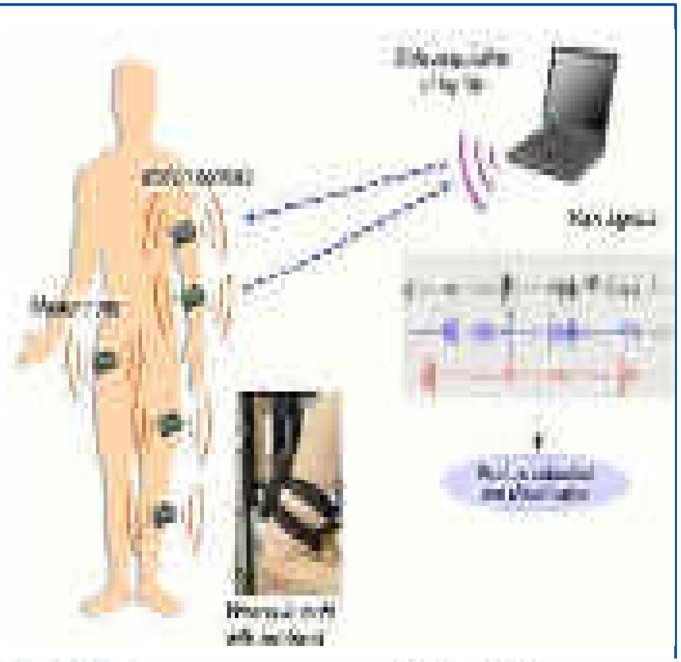
Goal: Automate and improve healthcare

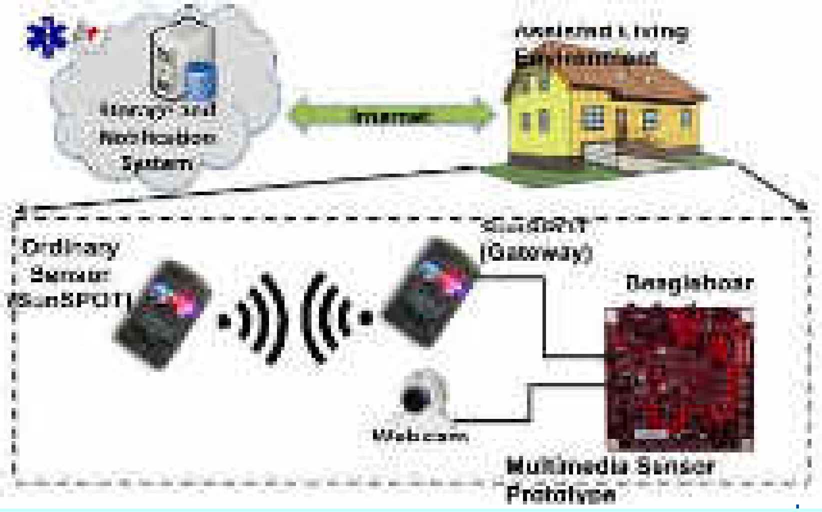
Multimodal Sensing Framework

- Monitor using heterogeneous sensors
- Fuse and process of multimodal data
- Efficient storage and fast notification

Implementation

- Case Study: Elderly fall detection
- Middleware, CouchDB server
- Validation using SunSPOT sensors





M. Di Francesco, S. Das, et al., "A Framework for Multimodal Sensing in Heterogeneous Multimedia Wireless Sensor Networks in Smart Healthcare," Proc. IEEE WoWMoM, 2011.

Smart Healthcare

- Collect context- / situation-aware data (activity, fall, movement, blood pressure, sugar level) via sensors
- Monitor long term and short term health trends
- Detect anomaly, identify potential health risks
- Provide automation and reminder assistance
- Assist in day-to-day activities and self-care-related needs
- Adapt to elderly and disables by learning and prediction

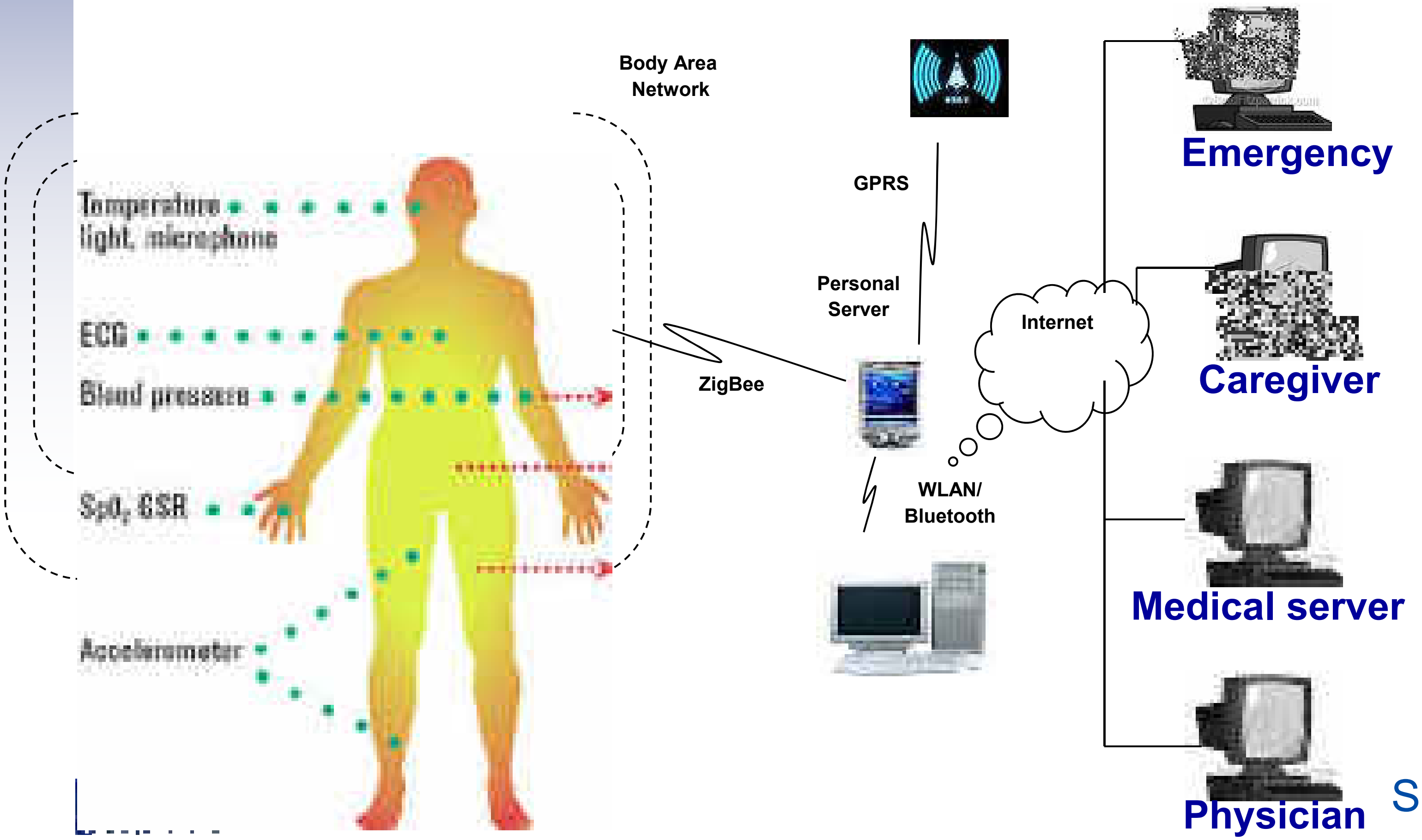
S. K. Das, "Smart Environments With Application to Healthcare," *Int. Conf. on Networking* (ICON), Singapore, Sept 2006 (Keynote Talk).

S. K. Das, "Health Monitoring in an Agent-Based Smart Home," *Int. Conf. on Smart Homes and Health Telematics* (ICOST), Sept 2004 (Keynote Talk).

S. K. Das, "Context Modeling of Smart Environments with Application to Healthcare and Security," *Int. Symp. Pervasive Wireless Computing* (ISPWC), San Juan, Feb 2007 (Keynote Talk).

Pervasive Healthcare

- Future pervasive healthcare environments will be saturated with computing and communication capabilities (wireless devices, sensors, etc.) to capture user contexts
- The goal is to provide smart health care decisions in an automated, context-aware, and proactive manner



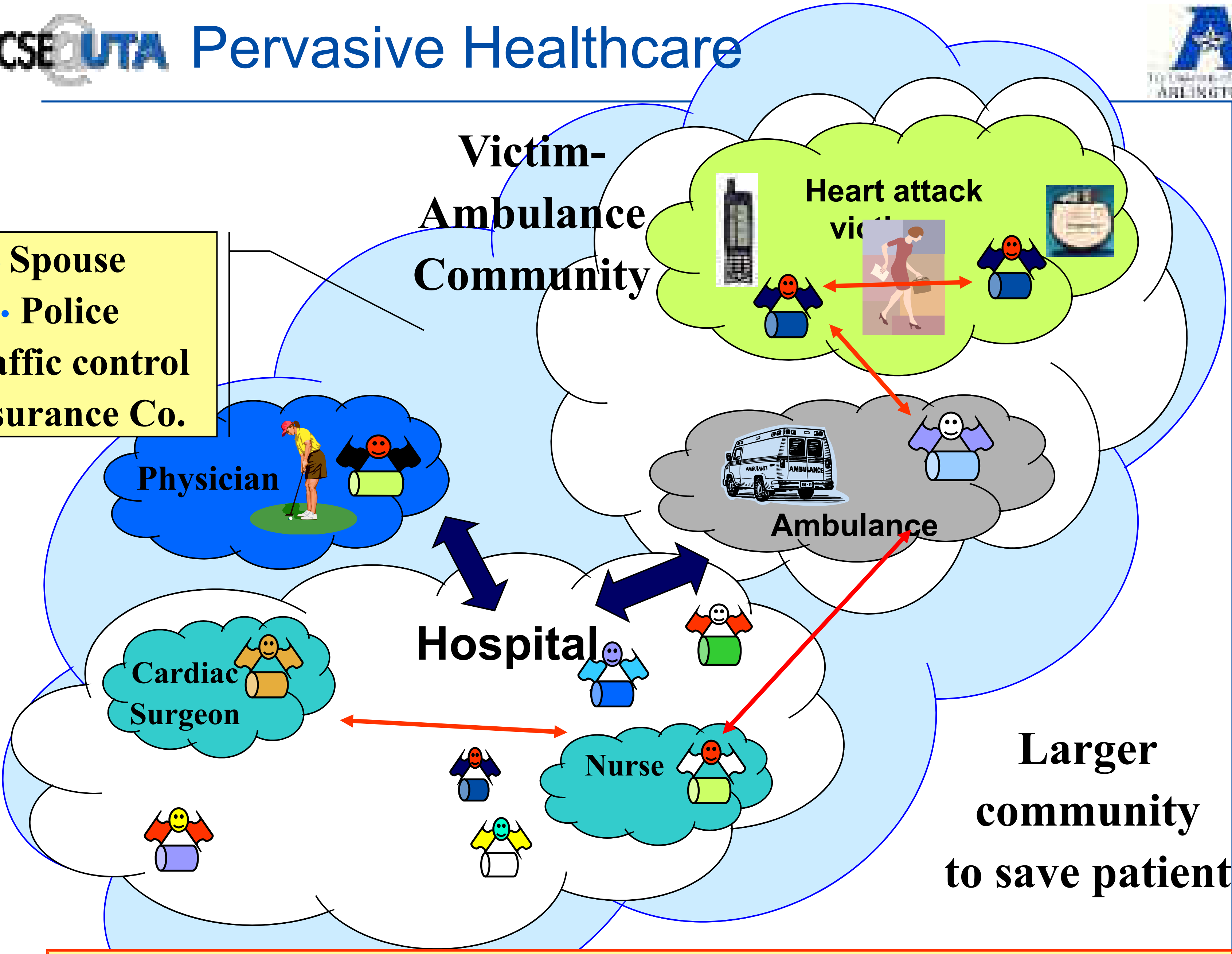
Pervasive Healthcare

- Consider a heart attack or car accident victim
- Desired actions
  - Coordinate with the ambulance, hospital, personal physician, relatives and friends, insurance, etc.
  - Control the traffic for smooth ambulance pass through
  - Prepare ER (Emergency Room) and the ER personnel
  - Provide vital medical records to physician
  - Allow the physician to be involved remotely …
- Just-in-Time, Automated, Mission-oriented Services:
  - What you want, when you want, where and how you want

M. Kumar, S. K. Das, et al., "PICO: A Middleware Platform for Pervasive Computing," *IEEE Pervasive Computing*, Vol. 2, No. 3, July-Sept 2003.

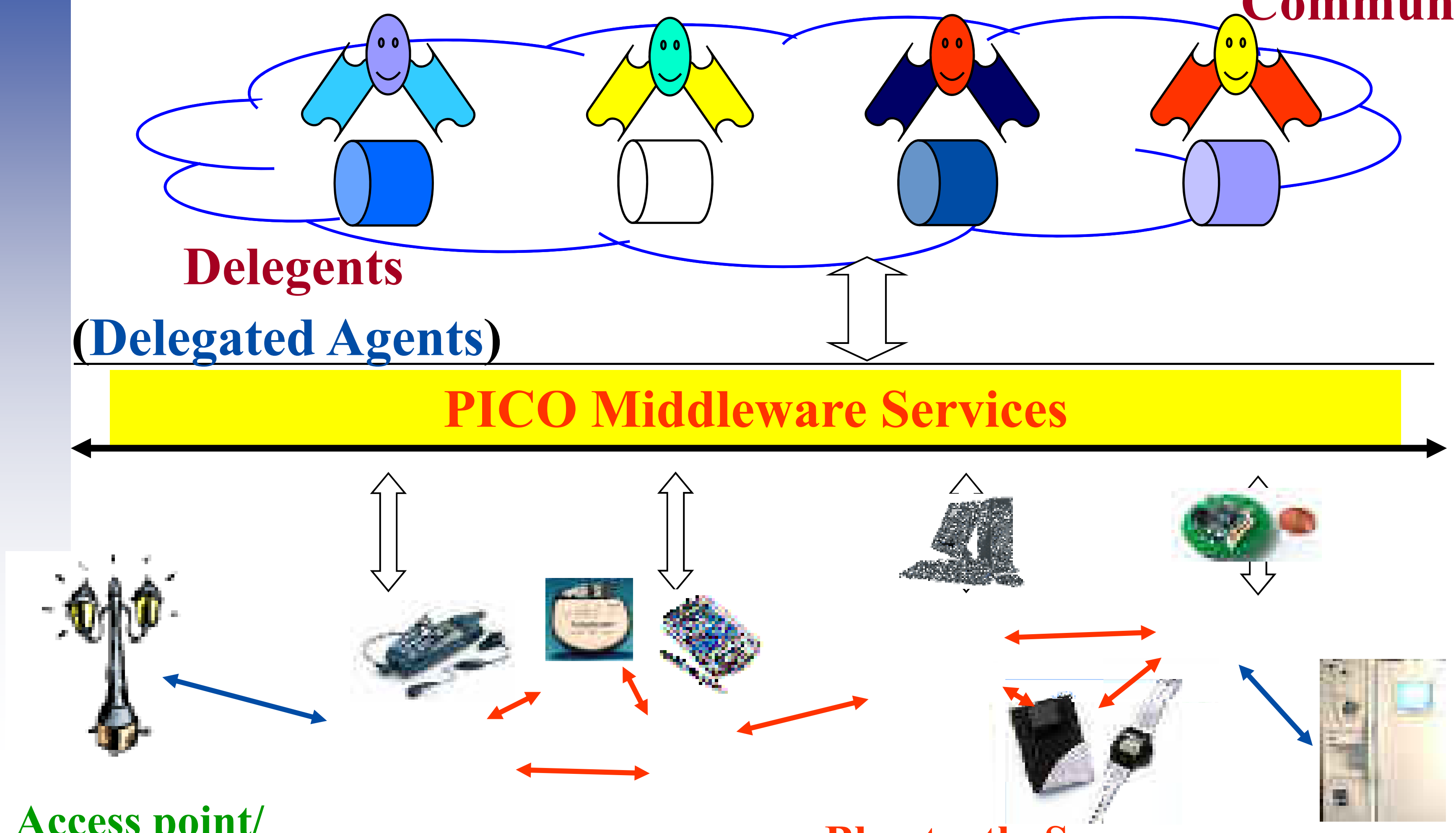
Pervasive Healthcare

- Spouse
- Police
- Traffic control
- Insurance Co.



NSF Project – Pervasive Information Community Organization (PICO): Internet Services of the Future, 2004-2007.

PICO: Pervasive Information Community Organization



Community

Delegents

(Delegated Agents)

PICO Middleware Services

Access point/ Gateway

Camileuns

Blue tooth, Sensor, 802.11, Cellular

Access point/ Gateway

Sajal K. Das

Middleware Research Challenges

- Information Acquisition, Dissemination and Service Discovery
  - Delegent *D(X)* representing Camileun *X* gather information on Camileun *Y*
  - Creation of static and dynamic communities, migration of delegents
  - Caching and pre-fetching of optimal information
  - Fast and reliable information storage and retrieval
- Context- or Location-Aware Computing: Mobility Management
  - Intelligent adaptation of both content and mode of delivery
  - Location or Mobility management of pervasive devices
  - Seamless coordination of information across multiple agents / networks
- Security, Trust and Privacy Mechanisms
  - Access control, authentication, authorization
- Quality of Service (QoS) Adaptation: Resource Management
  - Situation-aware monitoring and proactive resource management
  - Delegent profiles for just-in-time QoS adaptations

Novel Techniques

Energy-efficient, quality-adaptive framework

Context

Sample sensors to detect vital signs, activity (walking or sleeping), movement, behavior

Optimize sampling rate for minimum accuracy

Context aware multi-modal data fusion

Characterize uncertainty and ambiguity

Dynamic Bayesian Network for ambiguity resolution

Intelligent sensor information management

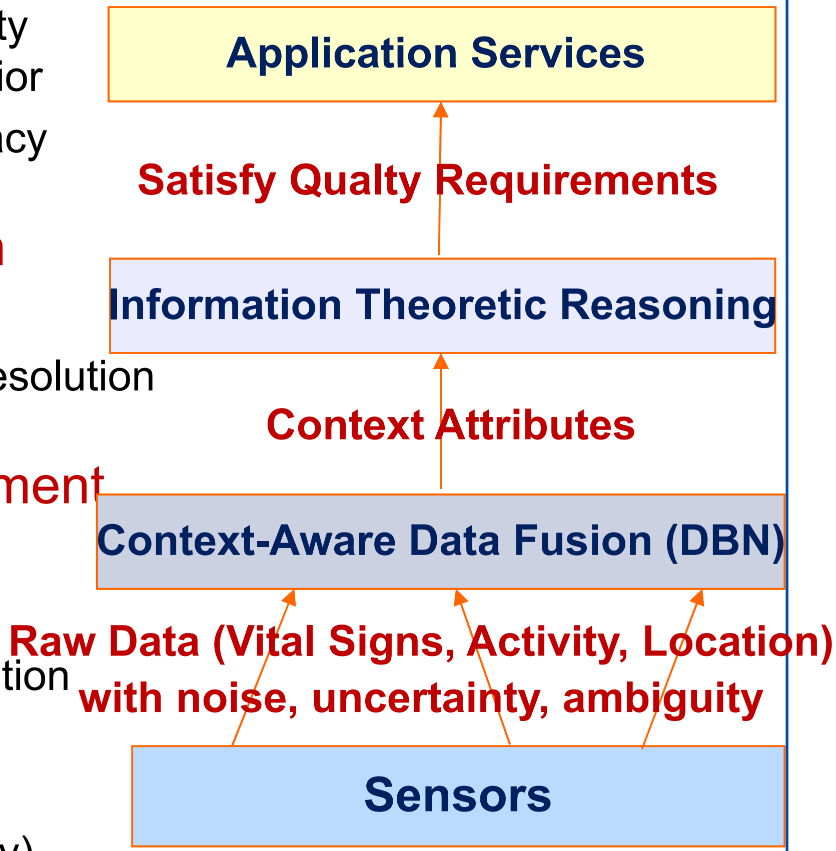
Information theoretic reasoning

Optimal sensor parameter selection

Reduction in ambiguity/error in state estimation

Quality-aware context determination

Tradeoff : Context accuracy vs. cost (energy)



Application Services

Satisfy Qualty Requirements

Information Theoretic Reasoning

Context Attributes

Context-Aware Data Fusion (DBN)

Raw Data (Vital Signs, Activity, Location) with noise, uncertainty, ambiguity

Sensors

N. Roy, A. Misra, C. Julien , S. K. Das, J. Biswas, "Energy-Efficient Quality Adaptive Framework for Multi-Modal Sensor Context Recognition", *Proc. IEEE Conf on Pervasive Computing and Communication*, 2011. (Best Paper Candidate). Extended version under revision, *ACM Transactions on Sensor Systems*, 2013.

Context-Aware Data Fusion

Top-down Inference

Given context state, select relevant ambiguity-reducing context attributes (e.g., time, blood sugar, frequency of getting up from bed)

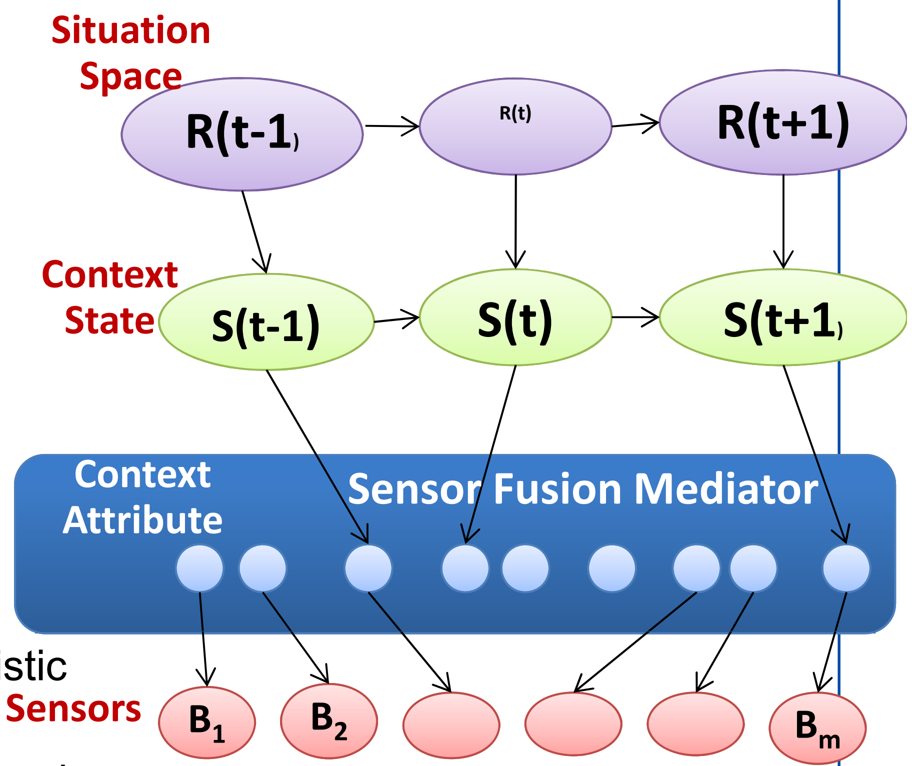
Bottom-up Inference

Given a set of context attributes, infer context states with varying (reported) ambiguities

Dynamic Bayesian Network (DBN)

Coherent and unified hierarchical probabilistic framework.

Sensory data representations, integration and inference



Compute Ambiguity-Reducing Utility:

$$V_i = \max_{i=0}^{K} \sum_{j=0}^{N} \left[p \left\langle a_j^R \middle| a_i^t \right\rangle \right]^2 - \min_{i=0}^{K} \sum_{j=0}^{N} \left[p \left\langle a_j^R \middle| a_i^t \right\rangle \right]^2$$

a_i^t = Context attribute

a_j^R = Situation space

Intelligent Sensor Management

- What information should each selected sensor send to enable the fusion center to

  - best estimate the current situation state

  - while satisfying the application's QoINF requirements and

  - minimizing the state estimation error?

- Model assumptions

  - Noisy observations across sensors are independently and identically distributed (i.i.d.) random variables

  - Each sensor has a source entropy rate *H(a_i);* i.e., to send data about attribute a_i requires *H(a_i)* bits of data

N. Roy, C. Julien, and S. K. Das, "Resource-Optimized Quality-Assured Ambiguous Context Mediation in Pervasive Environment," *Proceedings of QShine 2009* (Best Paper Award).

N. Roy, A. Misra, C. Julien , S. K. Das, J. Biswas, "Energy-Efficient Quality Adaptive Framework for Multi-Modal Sensor Context Recognition", *Proc. IEEE Conf on Pervasive Computing and Communication*, 2011. (Best Paper Candidate)

Information Theoretic Reasoning

- B = set of sensors, A = set of context attributes
- (B × A) matrix where *B_mi* = 1 if and only if sensor *m* sends attribute *a_i*
- Goal: Find the best (B × A) within capacity constraint Q that minimizes the estimation error of the situation space

$$\sum_m \sum_i H(a_i) * B_{mi} < Q \text{ and minimize } [P_e = P\{\overline{R} \neq R\}]$$

- Use Chernoff's theorem to maximize information content

  \- Ideally, each sensor sending exactly one bit of information is *optimal*

Implication: Multiple sensor fusion exceeds the benefits of detailed information from each individual sensor

Sajal K. Das

Quality-Aware Context Sensing

- Automated determination of context
  - We assume an underlying set of sensor data streams that can be aggregated into context data

- Estimation problem over multiple sensor data streams
  - Compute the best set of sensors + associated *tolerance* values
  - Satisfy a target *quality*
  - Minimize the *cost* of sensing

- Tolerance range
  - Measured in terms of a sensor's data reporting frequency
  - Ensure acceptable accuracy of the derived context

- Sensing Cost
  - Measured in terms of communication overhead (energy cost)

Quality of Inference Function (QoINF)

Error probability in estimating context state given uncertainty in sensor readings

- General form: (1 – average estimation error)

For a context C and a set θ of selected sensors:

$$QoINF_C(\theta, Q_\theta) = 1 - \sum_{x \in \Lambda_C} err_c(x, \{(s_i, q_i) : s_i \in \theta, q_i \in Q_\theta\})$$

where $Q_\theta = \{q_1, q_2, \cdots, q_\theta\}$ is the set of tolerance ranges for each sensor s_i in the set θ

Impact of Different Subsets of Sensors on QoINF (without tolerance ranges)

Quality vs. Cost Tradeoff

- **Cost measure:** the cost of using a sensor is a function of its assigned tolerance ran

$$COST\ (\theta, q_\theta) = \sum_{s_i \in \theta} c_i(q_i)$$

- When the cost is communication overhead, it scales with hop count, and we can use:

$$COST\ (\theta, q_\theta) = \kappa * \sum_{i \in \theta} \frac{h_i}{q_i^2}$$

  - where κ is a scaling constant and h_i is the hop count

- Formulate the *best* sensor selection as optimization problem:

$$(\hat{\Theta}, \hat{q}_\Theta)_{F_{\min}} = \overset{\arg\min}{\Theta \subseteq S, q_\Theta}, COST(\Theta, q_\Theta)$$

$$\text{such that } Quality_C(\hat{\Theta}, \hat{q}_\Theta) \geq F_{\min}$$

Quality vs. Cost Tradeoff

- Solving for arbitrary functions requires brute-force approach
- Certain forms are more tractable – when the QoINF of an individual sensor is expressed by an inverse exponential:

$$Quality_i = 1 - \frac{1}{\nu_i} e^{\frac{-1}{\eta_i q_i}}$$

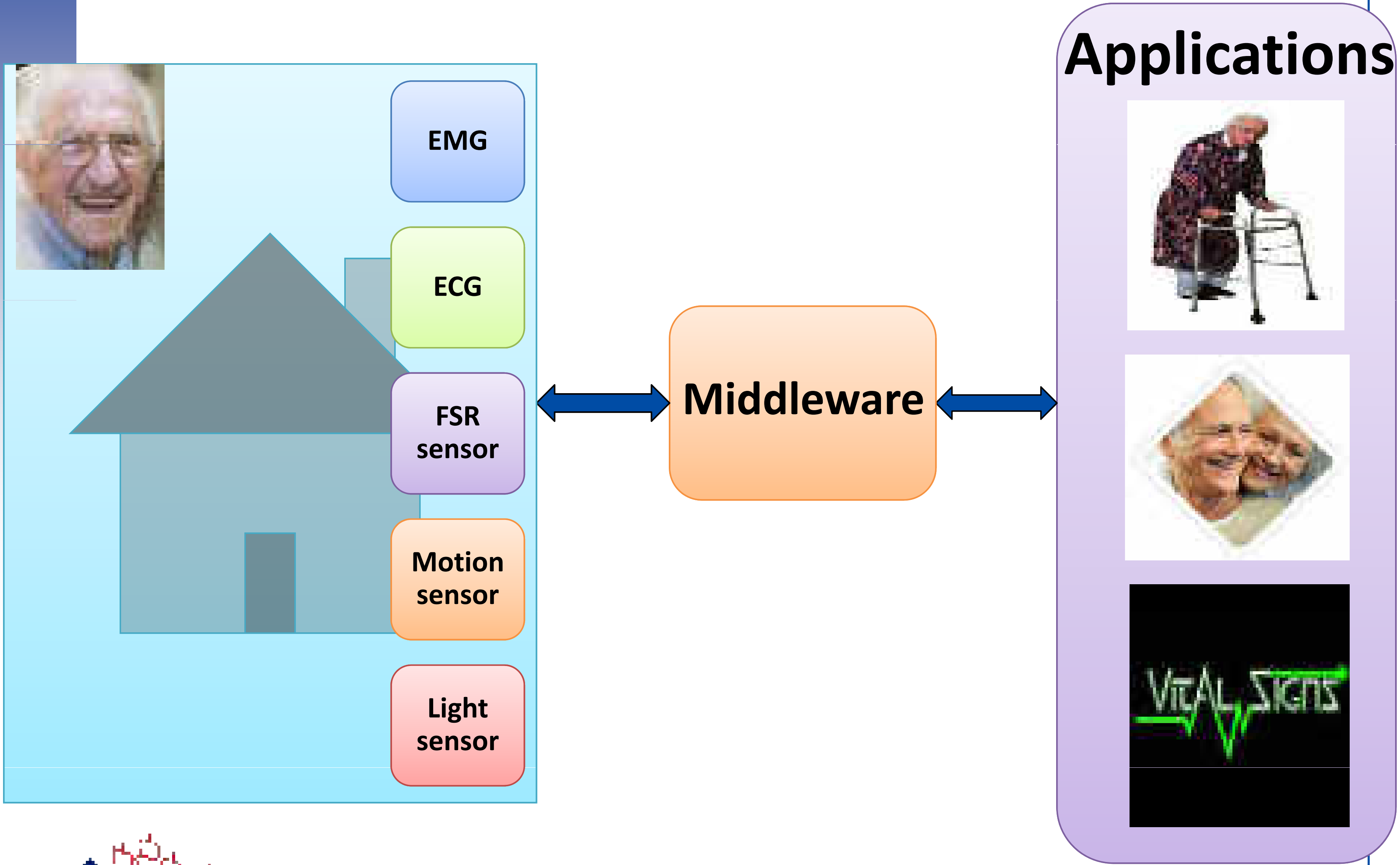
  - where η_i and ν_l are sensitivity constants for sensor s_i

- $\text{minimize } COST(\Theta, q_\Theta) \text{ subject to } Quality_C(\Theta, q_\Theta) \geq F_{\min}$

$$\text{minimize } \sum_{s_i \in \Theta} \frac{h_i}{q_i^{\,2}} + \lambda \left[1 - \prod_{s_i \in \Theta} \left[\frac{1}{\nu_i} e^{\frac{-1}{\eta_i q_i}} \right] - F_{\min} \right]$$

  - where λ is a Lagrangian constant for context C
  - we can find the optimal choices of q_i

Minimum-Cost Context Inference



EMG

ECG

FSR sensor

Motion sensor

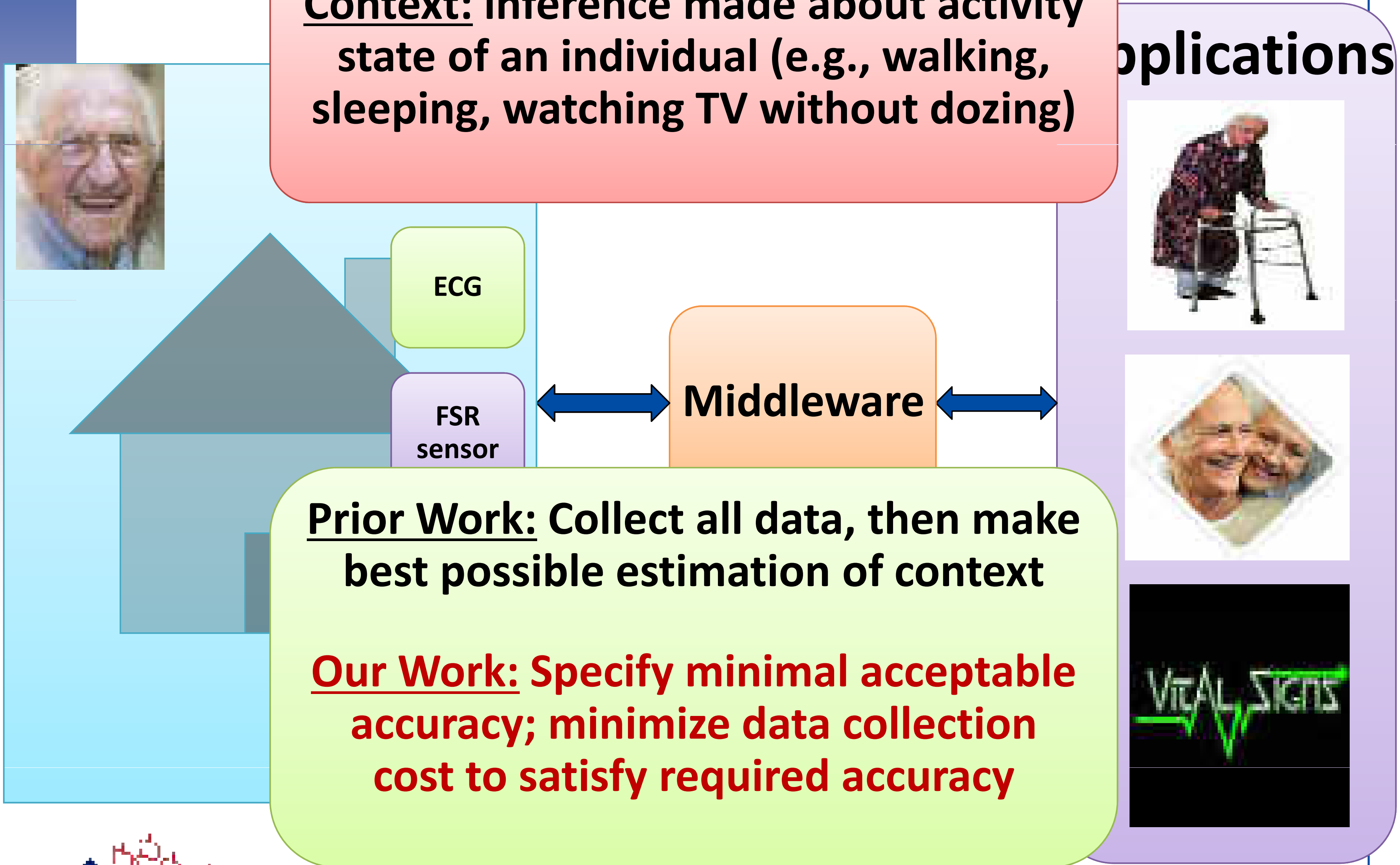
Light sensor

Middleware

Applications

Minimum-Cost Context Inference

<u>Context:</u> inference made about activity state of an individual (e.g., walking, sleeping, watching TV without dozing)

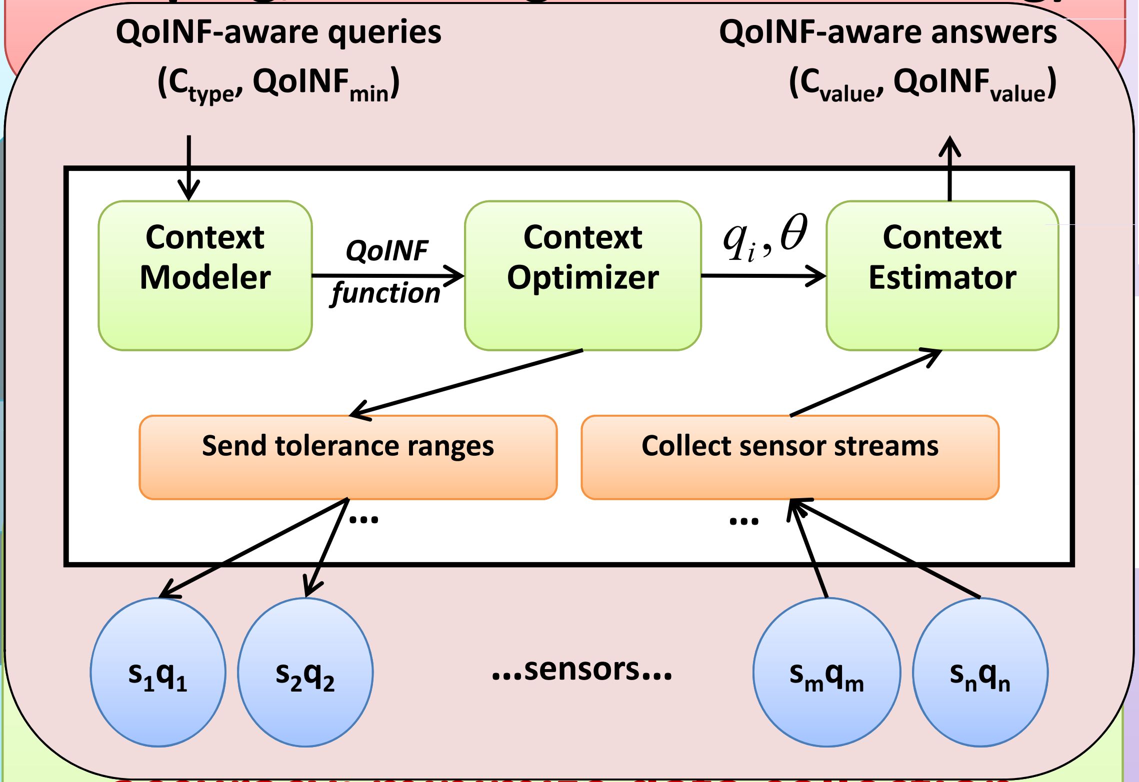


<u>Prior Work:</u> Collect all data, then make best possible estimation of context

<u>Our Work:</u> Specify minimal acceptable accuracy; minimize data collection cost to satisfy required accuracy

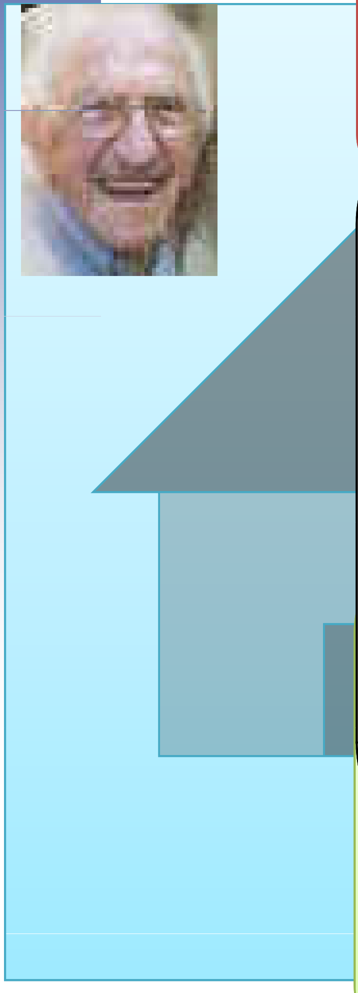
Minimum-Cost Context Inference

Context: inference made about activity state of an individual (e.g., walking, sleeping, watching TV without dozing)

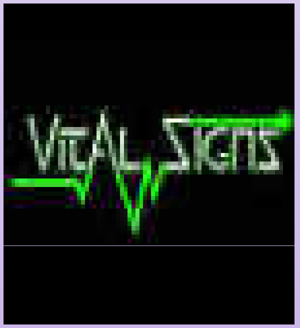


QoINF-aware queries (C_{type}, $QoINF_{min}$)

QoINF-aware answers (C_{value}, $QoINF_{value}$)

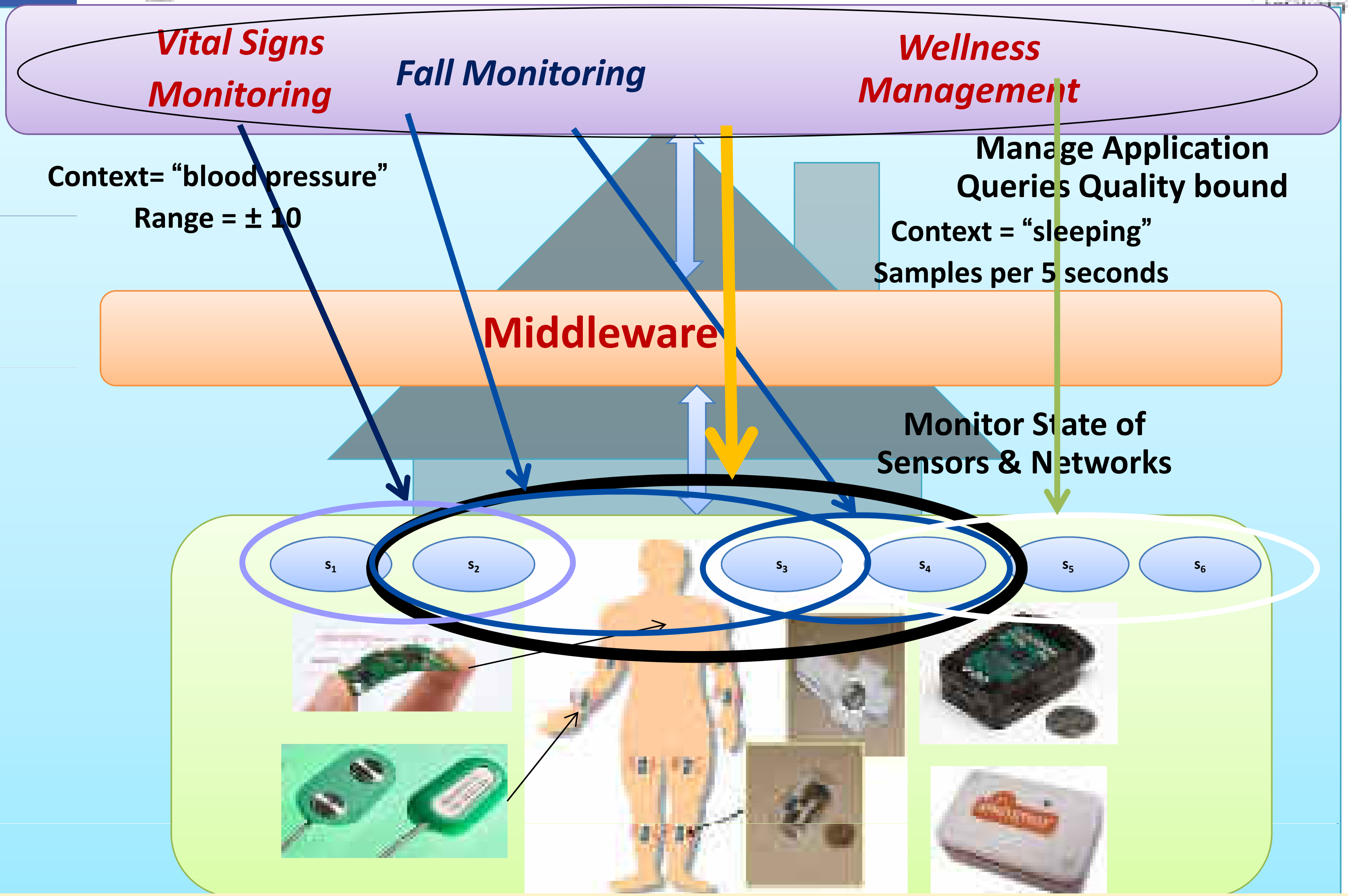


pplications



accuracy; minimize data collection cost to satisfy required accuracy

Smart Healthcare: Middleware



Vital Signs Monitoring

Fall Monitoring

Wellness Management

Manage Application Queries Quality bound

Context= “blood pressure”

Range = ± 10

Context = “sleeping”

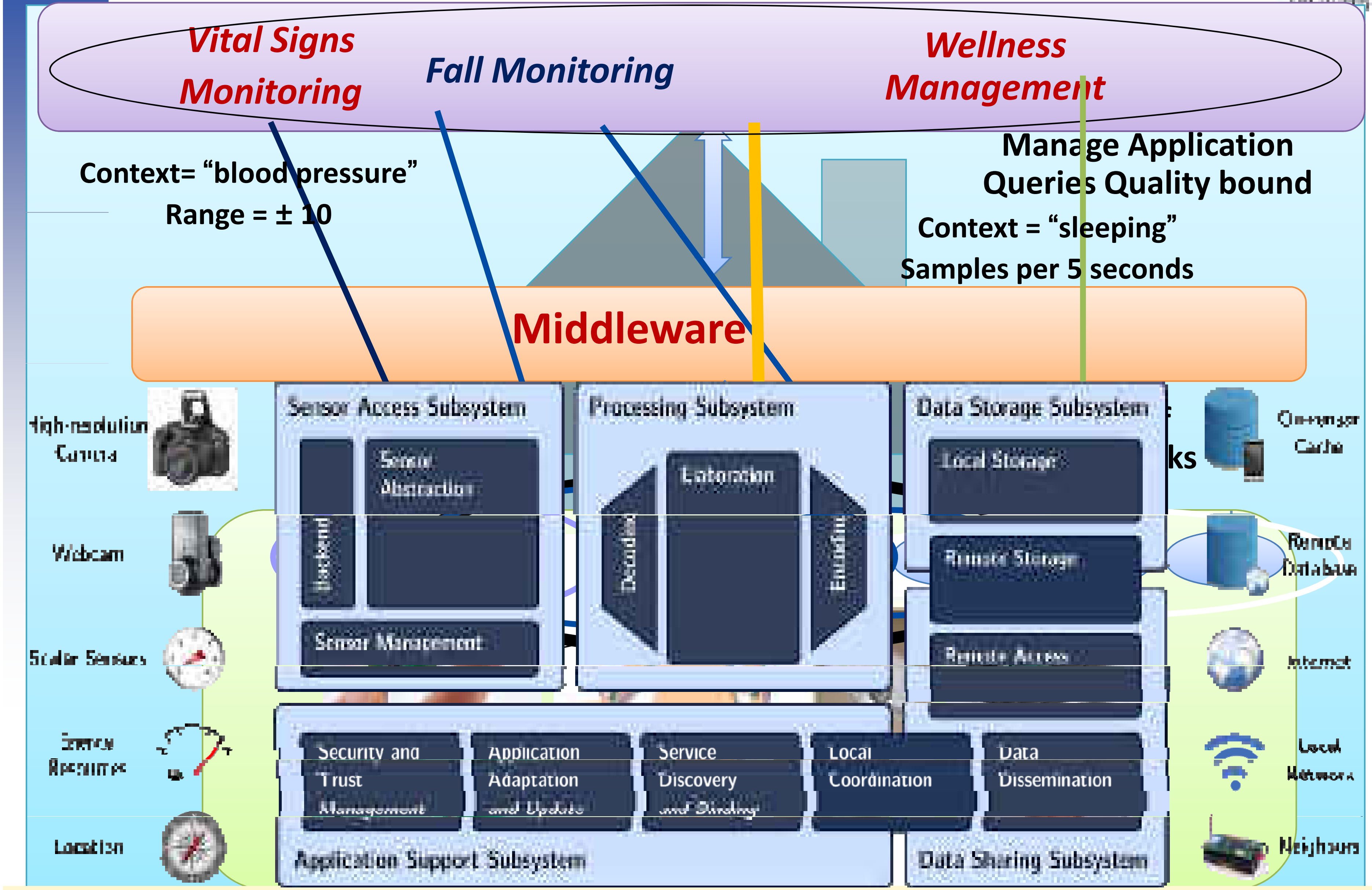
Samples per 5 seconds

Middleware

Monitor State of Sensors & Networks

N. Roy, S. K. Das, C. Julien, “Resource-Optimized Quality-Assured Ambiguous Context Mediation Framework in Pervasive Environments,” *IEEE Trans. Mobile Computing*, 11(2): 218-229, Feb 2012. (Best Paper, QShine 2009)

Smart Healthcare: Middleware



Vital Signs Monitoring

Fall Monitoring

Wellness Management

Context= “blood pressure”

Range = ± 10

Manage Application Queries Quality bound

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Samples per 5 seconds

Middleware

N. Roy, S. K. Das, C. Julien, “Resource-Optimized Quality-Assured Ambiguous Context Mediation Framework in Pervasive Environments,” *IEEE Trans. Mobile Computing*, 11(2): 218-229, Feb 2012. (Best Paper, QShine 2009)

SunSPOT Sensor Testbed

Accelerometer Sample Values
For different context states

Tilt Values (in degree)	Context State
85.21 - 83.33	*Sitting*
68.40 - 33.09	*Walking*
28.00 - 15.60	*Running*

Gyro Sensor Sample Values

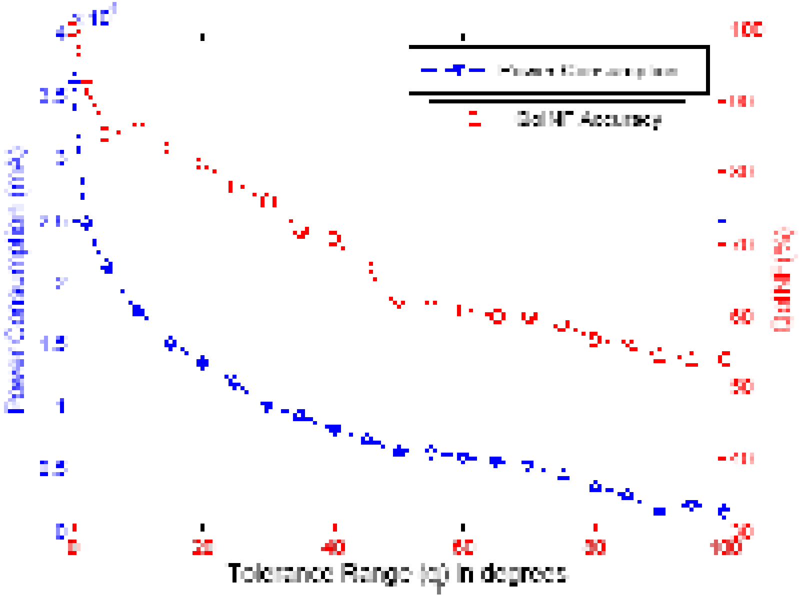
Avg. Angular Rotation Rate (degree / sec)	Context State
X-Rotational variation (Xout) = 150 - 350 Y-Rotational variation (Yout) = 150 - 350	Walking
X-Rotational variation (Xout) = 2 - 8 Y-Rotational variation (Yout) = 2 - 8	Sitting

Light Sensor Sample Values
for different context states

- 5 users engaged in different activities
  - sitting, walking, running for 30 days

QoINF vs. Energy Tradeoff

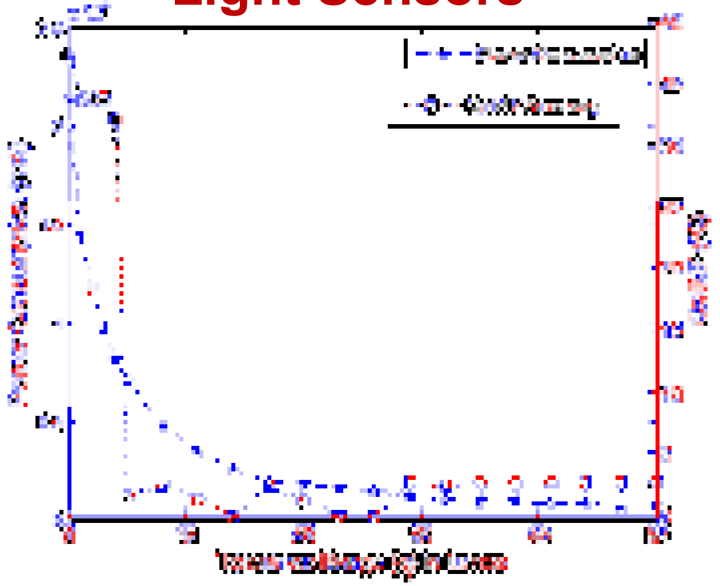
Motion Sensors



QoINF accuracy ~ 81% for q = 20

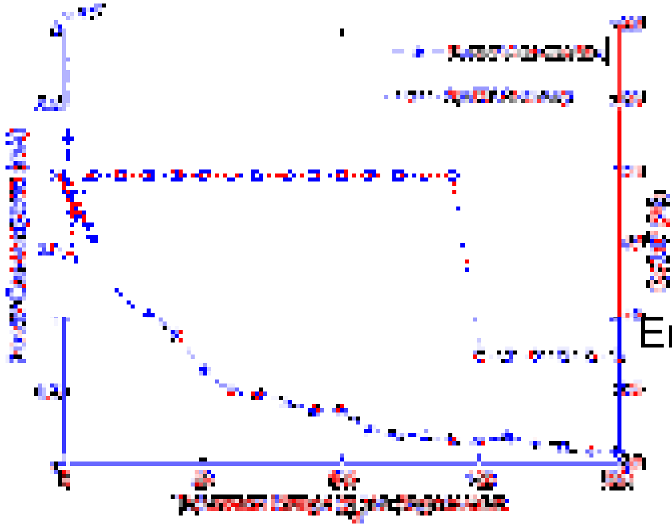
Energy consumption reduced ~ 63%

Light Sensors



~ 81% loss in accuracy for q = 4

Energy consumption reduced ~ 62%



Gyro Sensors

QoINF accuracy ~ 49% for q = 8

Energy consumption reduced ~ 62%

Sajal K. Das

Multi-modal Context Recognition

- H. J. Choe, P. Ghosh and S. K. Das, "QoS-aware Data Reporting in Wireless Sensor Networks," *Proc. 1st IEEE Workshop on Information Quality and QoS in Pervasive Computing* (IQ2S), Mar 2009.

- N. Roy, G. Tao, and S. K. Das, "Supporting Pervasive Computing Applications with Active Context Fusion and Semantic Context Delivery," *Pervasive and Mobile Computing*, 6(1): 21-42, Feb. 2010.

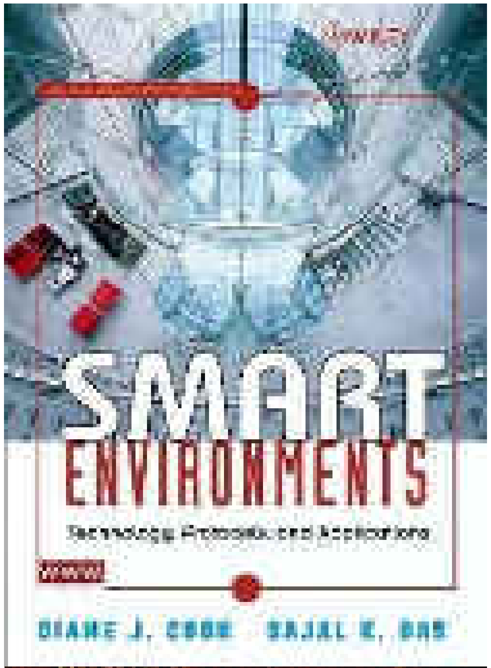
- N. Roy, A. Misra, C. Julien , S. K. Das, J. Biswas, "Energy-Efficient Quality Adaptive Framework for Multi-Modal Sensor Context Recognition", *IEEE Conf on Pervasive Computing and Communications*, Mar 2011. (Best Paper Candidate)

- N. Roy, S. K. Das, C. Julien, "Resource-Optimized Quality-Assured Ambiguous Context Mediation Framework in Pervasive Environments," *IEEE Transactions on Mobile Computing*, 11(2): 218-229, Feb 2012. (Best Paper, QShine 2009)

- N. Roy, A. Misra, S. K. Das, C. Julien, and D. J. Cook, "Quality- and Energy-Sensitive Determination of Multiple Contexts in Pervasive Computing Environments," *ACM Transactions on Sensor Systems*, under revision, 2013.

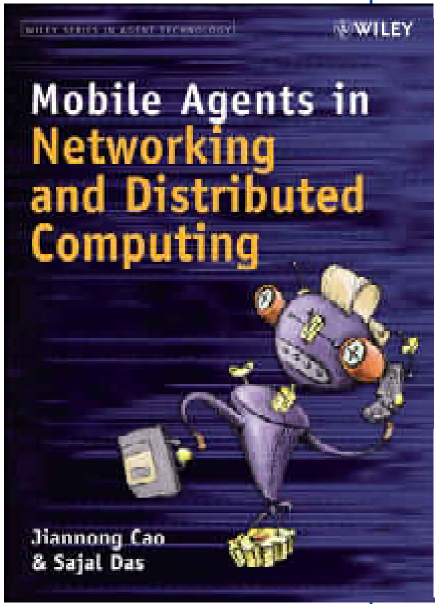
Summary

ACTIVITY	TOTAL
h-index	54
Research Grants	$8M +
Journal Publications	236
Conference Publications	389
Ph.D. Graduates	34
M.S. Thesis (BS Honors)	29 (6)
Keynote Talks (Tutorials)	23 (16)
Patents Awarded (Pending)	5 (3)
Books	3
Book Chapters	48
Best Paper Awards (Nominee)	9 (5)
Outstanding Dissertations	10
Outstanding MS Thesis (BS)	7 (3)
Journal Editorship (EIC)	11 (2)


SMART ENVIRONMENTS

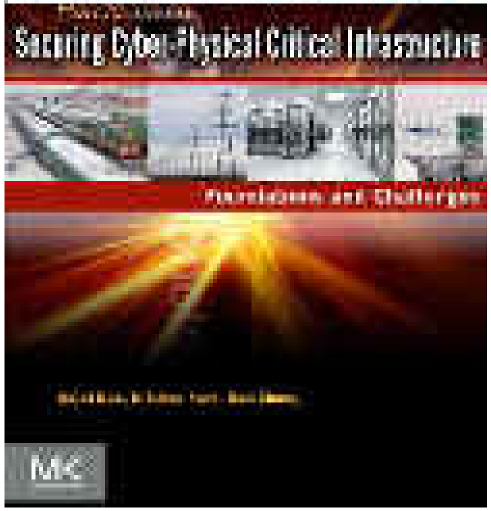
Technology, Protocols, and Applications

DIANE J. COOK SAJAL K. DAS


WILEY

Mobile Agents in Networking and Distributed Computing

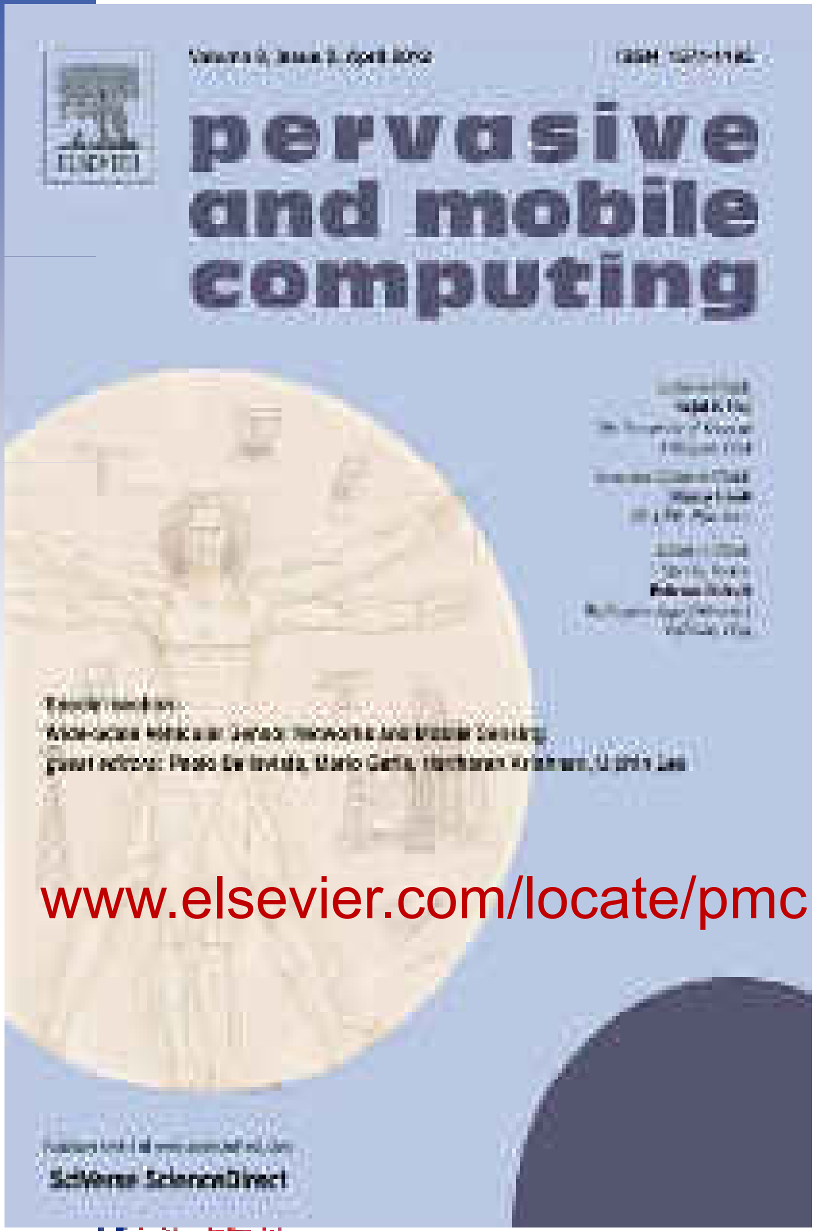
Jiannong Cao & Sajal Das


Securing Cyber-Physical Critical Infrastructure

Foundations and Challenges

MK


pervasive and mobile computing



pervasive and mobile computing

www.elsevier.com/locate/pmc

ICDCN 2014

15th Int'l Conference on Distributed Computing and Networking

Amrita Univ, Coimbatore, India

January 4-7, 2014

www.icdcn.org (Deadline: July 19, 2013)

IEEE PerCom 2014

12th Int'l Conf on Pervasive Computing

Budapest, Hungary

March 24-28, 2014

www.percom.org (Deadline: Sept 21, 2013)

IEEE WoWMoM 2014

15th Int'l Symp. on a World of Wireless Mobile Multimedia Networks

Sydney, Australia

June 16-19, 2014 (Deadline: Nov 29, 2013)

www.ieee-wowmom.org